Daniel J. Hedequist
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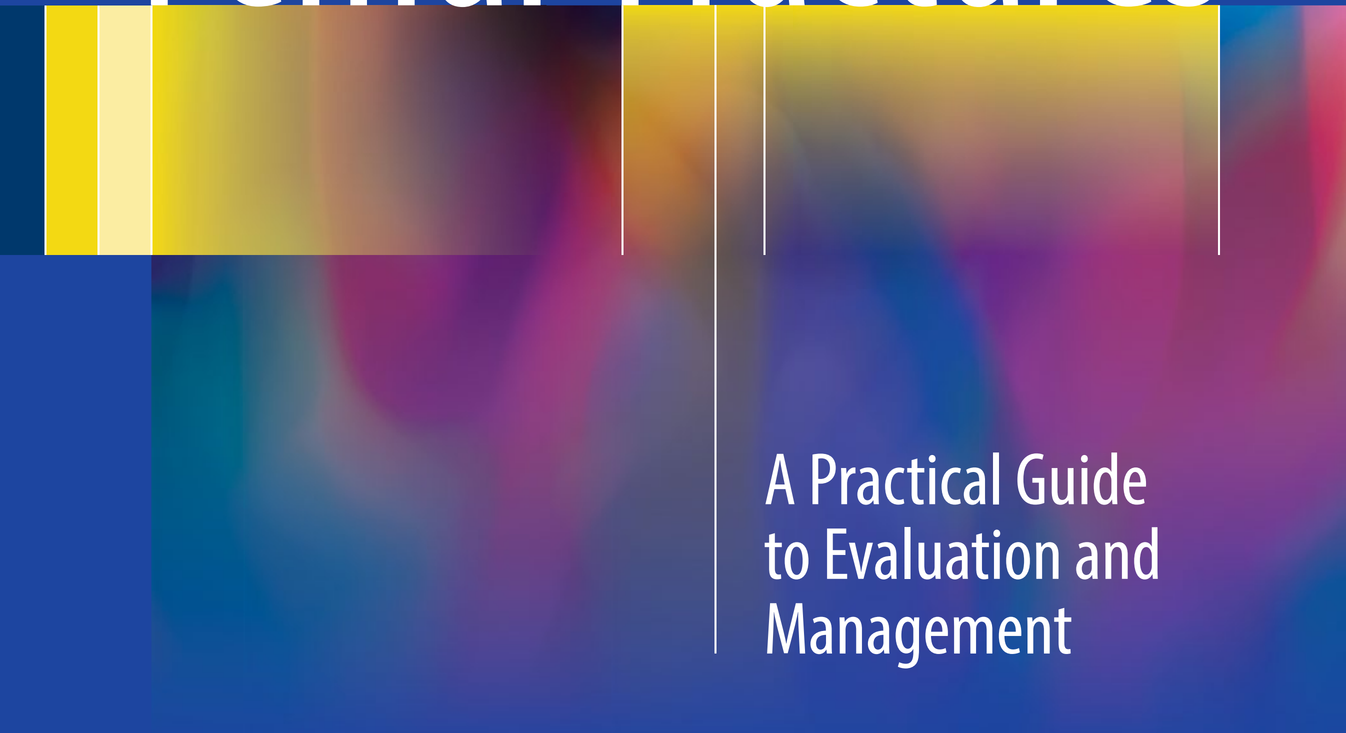
Editors

Pediatric Femur Fractures



A Practical Guide to Evaluation and Management

Springer

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Foreword

Finally, a comprehensive text devoted to pediatric femur fractures! The femur fracture chapters in pediatric fracture and pediatric surgical technique textbooks are typically the most frequently scoured by orthopedic residents, fellows, general orthopedic surgeons, orthopedic traumatologists, and pediatric orthopedic surgeons. The reasons are that these fractures are common, they can be challenging to manage, treatment methods are constantly changing, and they have the potential for poor outcomes and severe complications (not to mention lawsuits!).

I don't feel that old, but the management of pediatric femur fractures has changed dramatically just over the course of my career over the last 20 years. When I was a junior resident at Boston Children's Hospital in the early 1990s, we cared for multiple patients with femur fractures on the hospital floor on any given day, hanging in skeletal traction awaiting delayed spica casting. Since then, we have witnessed the rapid adoption of new techniques, including immediate spica casting, external fixation, flexible intramedullary nailing, submuscular plating, and trochanteric-entry rigid intramedullary nailing. In addition, there has been a proliferation of clinical practice guidelines. This adoption of new techniques in the management of pediatric femur fractures has been dramatic and, at times, has occurred faster than our ability to obtain comparative effectiveness data. It is essential to keep the ultimate outcomes of importance in mind when managing pediatric femur fractures: union, alignment, maintenance of length, function, burden of treatment on child and family, and, increasingly, considerations of cost.

I commend Drs. Hedequist and Heyworth on this excellent text. In addition to striving to be masters of management of pediatric femur fractures, they have assembled an impressive collection of pediatric orthopedic surgeons who are recognized experts in this injury. The text is unique in how comprehensive it is, covering the essential concepts of growth and imaging of the femur as well as the treatment of femur fractures in *all* pediatric age groups, from infants through older adolescents. In addition, all locations are covered in the femur, from the femoral head to distal femoral intra-articular fractures, with individual chapters for each of the many different treatment methods for diaphyseal femoral fractures. The individual chapters include basic dogma, literature review, controversies, and management pearls.

I look forward to seeing this textbook in hospital libraries, personal offices, on call rooms, and OR lockers. This text will give the reader the knowledge and pearls to treat this challenging fracture with skill and wisdom, resulting in good outcomes and the avoidance of complications, which will benefit the child over their lifetime.

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Preface

This textbook originated from the idea that few pediatric fractures can impose changes upon the lives of affected children and their families as significantly as femur fractures. These injuries present a great challenge in avoiding complications, preventing permanent disability, and returning patients to their previous state of health and activity. In the same light, few topics in pediatric orthopedic trauma have evolved as rapidly, in terms of the principles of evaluation and management, as femur fractures. An explosion of literature and new technology has emerged in the last two decades to forward our thinking on optimizing femur fracture care in children.

Our goal was to consolidate the many pieces of the complex puzzle of pediatric femur fracture management into a comprehensive and up-to-date resource for clinicians managing these injuries. We hope we have succeeded in providing a highly readable and exhaustive evidence-based reference tool. The chapters herein are designed to simplify the most complex principles and elucidate the range of techniques utilized to heal the broken femur of a child.

We would like to express our most sincere appreciation for the large number of surgeons colleagues from across the country who worked tirelessly to produce the expert material contained in these chapters. We would also like to acknowledge our mentors at Children's Hospital in Boston who have always adhered to the principle of strong clinical abilities supported by academic research and teaching. Special mention needs to be given to James Kasser MD, who, through clinical mentorship, societal leadership, and editorial experience, has always stressed the importance of expert pediatric trauma care to countless residents, fellows, and colleagues throughout the United States.

Finally, and most importantly, we would like to thank our wives and children for the patience and support to allow us to pursue the academic endeavors, such as this textbook, that may help our generation and future generations to provide the best orthopedic care possible for injured children and their families.

Boston, MA, USA

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The Pediatric Femur: Development, Growth, and Surgical Anatomy

1

Collin May and Samantha Spencer

Introduction

The development of the adult limb is part of a coordinated and highly regulated series of events starting post-fertilization and leading through cell division, gastrulation, organogenesis, limb bud formation, patterning, and final cell differentiation. Skeletal elements form through a combination of endochondral and intramembranous ossification, with the soft tissue envelope developing in concert to form a functioning and highly specialized unit. Growth in different parts of the body occurs at different rates and in different sequences, yet the vast majority of individuals reach skeletal maturity with limbs of proportionate length and alignment.

Advances in our understanding of the molecular pathways governing limb development have offered insight into many of the pathologic processes involved in limb anomalies and developmental deformities. New therapies and approaches to treating growth disturbance in the limbs have created exciting alternatives for children and adults affected by congenital or acquired limb differences.

This chapter describes the embryologic processes leading to limb development, followed by a discussion of the anatomy and function of the growth plate. General growth concepts are reviewed, highlighting the patterns of growth specific to the lower extremity and the femur. Pathologic growth states following fracture of the femur, as well as the various treatment options for growth abnormalities are outlined in detail. Terms and conditions of particular interest have been italicized to help the reader return to the chapter as a reference guide and facilitate its role as a teaching tool for trainees.

Embryology

The *gestational period* in humans has typically been divided into embryonic and fetal stages, with the *embryonic stage* defined as the 8 weeks following fertilization and the *fetal stage* from 8 weeks to birth. The embryonic stage can be further subdivided into the "pre-embryonic period" and "true embryonic period." The *pre-embryonic period* encompasses the early events of fertilization and implantation, through gastrulation and the formation of the bi- and tri-laminar embryonic disk (weeks 1–3). The *true embryonic period* spans weeks 4–8 and it is during this time that the organ systems are formed and the overall body plan is established. Rapid cell division, movement, and differentiation occur during the

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true embryonic period, which makes the embryo particularly vulnerable to the harmful effects of teratogens. Weeks 9 to delivery comprise the fetal stage, important for the growth and maturation of newly developed organ systems [1].

Pre-embryonic Period

Following fertilization, the initial events of the pre-embryonic period involve coordinated cell divisions in which the initial single-cell *zygote* produces a ball of eight smaller cells termed the *blastula*. Further division produces the 16-cell *morula*, followed by the 32-cell *blastocyst*. By the blastocyst stage, an inner and outer cell layer has formed (*embryoblast* and *trophoblast*) that will determine embryonic and extraembryonic tissues, respectively (Fig. 1.1) [2]. The blastocyst implants on the uterine wall at approximately day 6 and the trophoblastic outer cells differentiate into two distinct layers, the *syncytiotrophoblast* and *cytotrophoblast*. The syncytiotrophoblastic cells invade the uterine endometrium and the mitotically active cytotrophoblast adds to the growing syncytiotrophoblast. As implantation of the blastocyst takes place, morphologic changes are occurring to the embryoblastic cells, with differentiation into two distinct cell layers, the *hypoblast* and *epiblast*. These two cell types are arranged into a flat plate of cells, called the bilaminar *embryonic disk* (Fig. 1.2) [3–5].

Gastrulation

By the third week of gestation the cells of the developing embryo begin to rearrange themselves to establish the overall body plan as well as form the three germ layers (ectoderm, mesoderm, and endoderm), which are the precursor cells to all of the body's tissues [6–8]. The initial event of gastrulation is the formation of the *primitive streak* on the dorsal surface of the bilaminar embryonic disk (Fig. 1.3). Epiblastic cell proliferation along the midline forms a thickened band of tissue—the primitive streak—that establishes the longitudinal axis of the embryo, as well as its cranial and caudal ends. A groove develops in the primitive streak due to invagination of neighboring epiblastic cells, which proliferate and migrate through the groove to form the three embryonic germ layers (Fig. 1.4) [9, 10]. Each of the germ layers gives rise to specific tissues: *ectoderm* is the source of the epidermis and nervous tissues, *mesoderm* forms connective tissue (including muscle, bone, and blood), and *endoderm* gives rise to the linings and glandular tissues of the lungs and intestinal tracts.

True Embryonic Period

The true embryonic period encompasses the fourth to eighth weeks of development and is also termed the period of organogenesis. It is during this period that the three germ layers begin to give rise to the various body tissues.

Neurulation

The formation of the *neural tube* (which will eventually become the nervous system) begins with a complex interplay between mesodermal cells and ectoderm in the midline. A prespecified region of ectoderm is induced to thicken and form the *neural plate*, followed by elevation of the lateral edges of the plate to form the *neural folds*. The depressed middle of the neural plate forms the *neural groove*. As the neural folds move toward one another in the midline, they fuse and result in the neural tube. The neural tube closes from its middle to the cranial and caudal ends (Fig. 1.5). Failure to close at the cranial end leads to anencephaly and at the caudal end to neural tube defects such as myelodysplasia [11].

Neural Crest

As the neural folds come together to fuse and form the neural tube, cells at the most dorsal portion, or crest, of the neural tube dissociate and form a special population, the neural crest [12, 13]. Neural crest cells migrate throughout the organism to form sensory ganglia, sympathetic neurons, Schwann cells, and melanocytes [14–17].

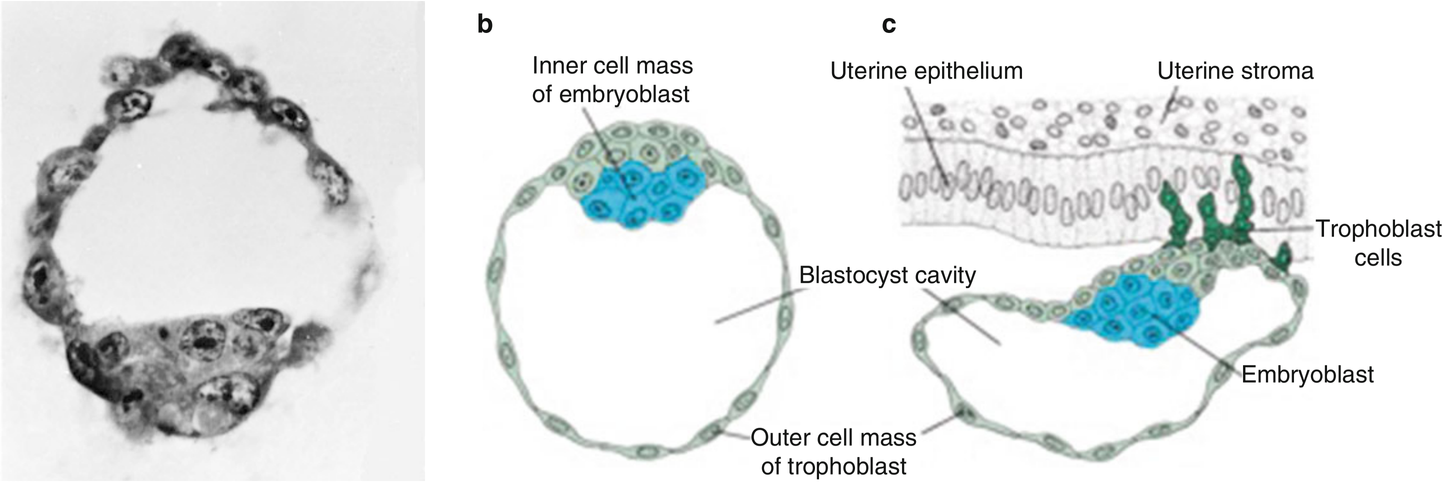


Fig. 1.1 (**a**) Pathologic section of embryo at the blastocyst stage, showing inner cell mass and trophoblast. (**b**) Schematic representation of same. (**c**) Blastocyst at approximately day 6 post-fertilization showing trophoblast implantation in uterine stroma. Reprinted with permission from Sadler TW. Langman's Medical Embryology. 11 ed. Baltimore, MD: Lippincott Williams & Wilkins; 2010. Figure 3.10, p 42 [2]

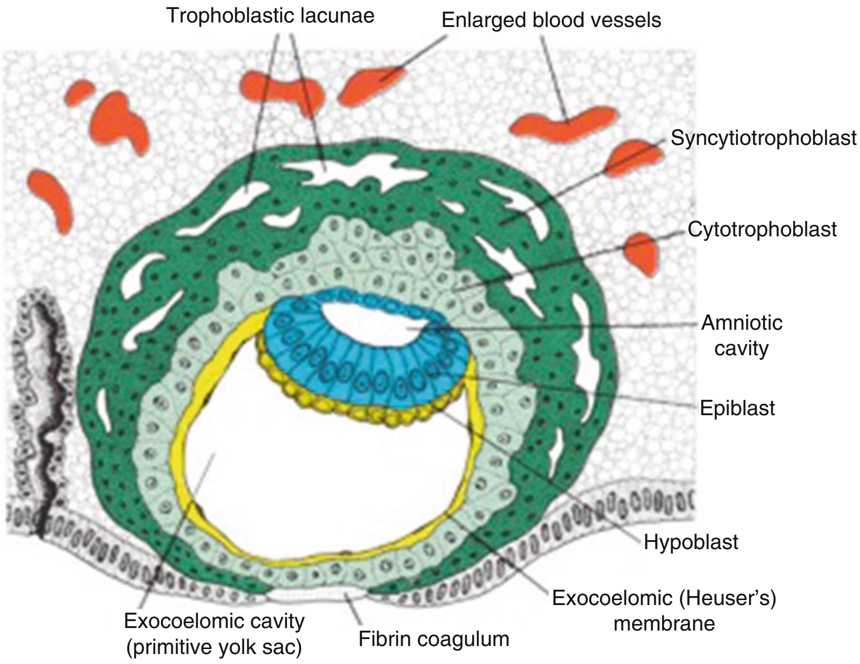


Fig. 1.2 Schematic of a 9-day human blastocyst. Syncytiotrophoblast has eroded into uterine stroma endothelial lining and developed lacunae. Cells of the embryoblast have differentiated into a bilaminar disk consisting of columnar epiblast and cuboidal hypoblast cells. Reprinted with permission from Sadler TW. Langman's Medical Embryology. 11 ed. Baltimore, MD: Lippincott Williams & Wilkins; 2010. Figure 4.8, p 4 [2]

Mesodermal Differentiation

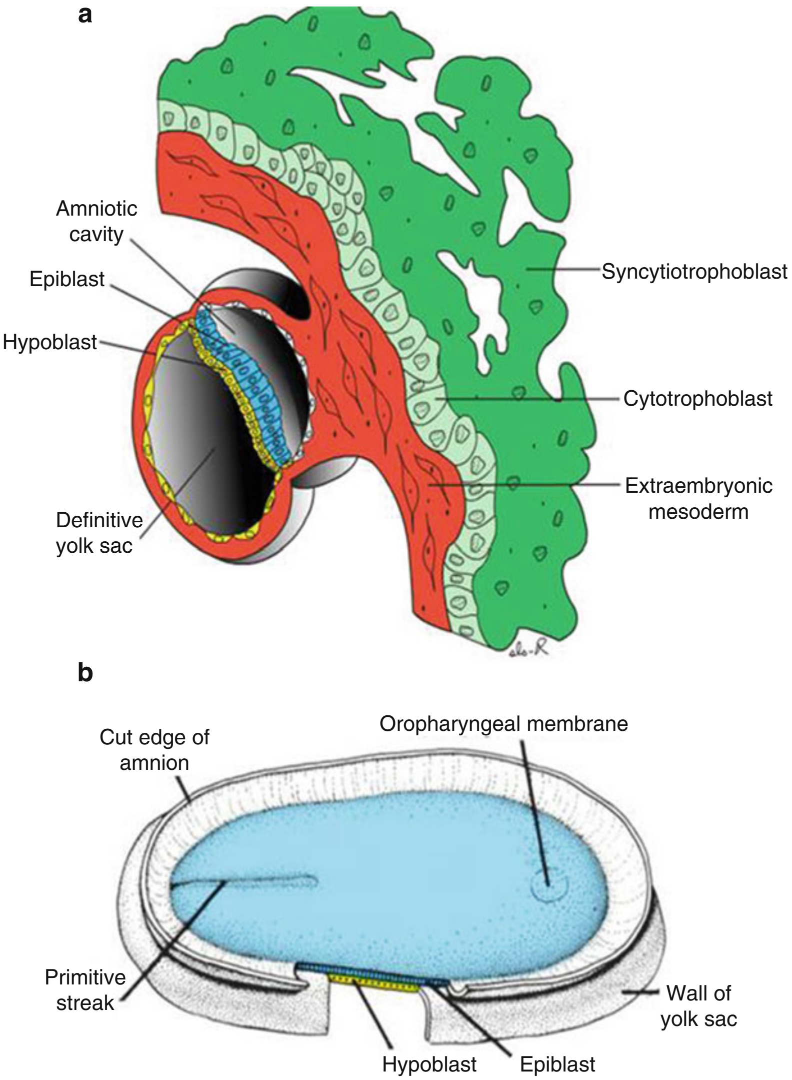
As neurulation is taking place, cells of the mesodermal germ layer begin to organize themselves along the midline adjacent to the neural tube (*paraxial mesoderm*), and more laterally (*lateral plate mesoderm*) [18]. Through cyclic expression of various gene products, including members of the *Notch* and *WNT* signaling pathways, paraxial mesoderm begins to segment into paired units called *somites* [19, 20]. Each somite pair will eventually give rise to the vertebrae and ribs, as well as muscle and dermis of the back and body wall and most of the limb musculature (Fig. 1.6). Adjacent lateral plate mesoderm is responsible for producing the bones and connective tissues of the limbs, as well as the ventral body wall and lining of body cavities [21–24].

Limb Development

By day 28 following fertilization, the *upper limb bud* begins to become visible as an outpouching of tissue from the ventrolateral body wall, with the *lower limb bud* forming 2 days later. The limb bud at this stage consists of a loose mesenchymal cell core derived from lateral plate mesoderm, and is covered by a layer of ectoderm. The mesenchymal cells form the skeletal elements and connective tissues of the limb, including cartilage, bone, tendon, and blood vessels. Somite-derived mesodermal cells will form the muscles of the limb, and peripheral nerves arise from the neural crest (Fig. 1.7) [21, 25].

The ectodermal cells overlying the distal tip of the limb bud thicken and take on a special role, that of the *apical ectodermal ridge* (AER) (Fig. 1.8). Through secretion of *fibroblast growth factors* (FGFs), the AER induces adjacent mesenchymal cells to rapidly proliferate and remain in an undifferentiated state [26–28]. The region of mesenchyme adjacent to the AER is known as *the progress zone* [29]. As the limb bud elongates, more proximal cells become farther from the inductive effects of the AER, and thus begin to differentiate into condensations of cells that form the cartilage templates of the skeletal elements. This sequence ensures the development of the limb in a proximal-to-distal direction [30, 31].

Fig. 1.3 (**a**) Schematic embryo at the beginning of the third week. (**b**) Representative view of the germ disk at the beginning of the third week, with amniotic cavity open, looking down on the dorsal side of epiblast. Primitive streak has formed in the caudal end. Reprinted with permission from Sadler TW. Langman's Medical Embryology. 11 ed. Baltimore, MD: Lippincott Williams & Wilkins; 2010; p. 56



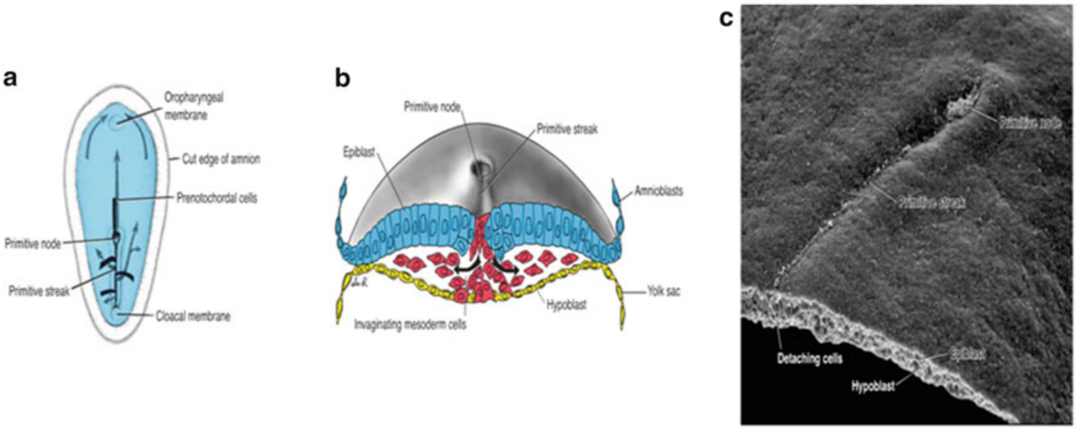


Fig. 1.4 Cell movements during gastrulation. (**a**) Cells migrating through primitive streak and node will become the precursors of mesoderm and endoderm. (**b**) Transverse section through embryo shows epiblast invagination. (**c**) Dorsal view of embryo at stage depicted in **b**. Reprinted with permission from Sadler TW. Langman's Medical Embryology. 11 ed. Baltimore, MD: Lippincott Williams & Wilkins; 2010; p 57

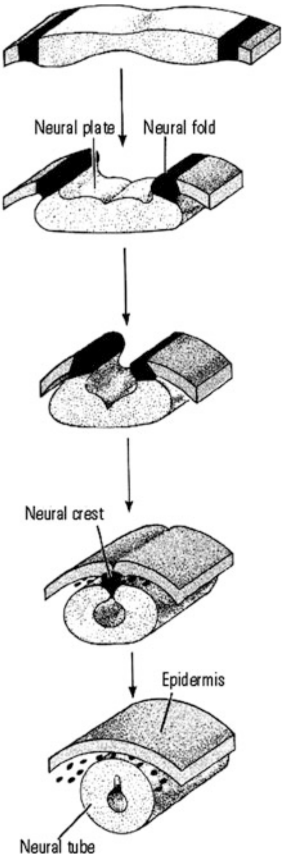


Fig. 1.5 Diagram representing neural tube formation. Neural folds become elevated and migrate toward one another, and the depressed midregion forms the neural groove. Folds fuse to form the neural tube, with connecting neural crest cells. This process begins centrally and extends cranially and caudally. Reprinted with permission from Developmental Biology, 3rd ed. Sunderland, MA: Sinauer Associates, Inc. 1991

Limb Patterning

As the limb bud continues to grow outward, the anterior–posterior axis (radial-ulnar axis in the upper limb or tibial-fibular axis in the lower limb) is controlled by signals from another specialized region, the *zone of polarizing activity* (ZPA) [32]. This group of mesenchymal cells located posteriorly on the limb bud is the source of *retinoic acid* (vitamin A) which initiates expression of the secreted protein *Sonic hedgehog* (Shh) (Fig. 1.9) [33]. Animal experiments involving grafting of the ZPA portion of the limb bud show that if placed on the anterior portion of a limb already expressing a normal ZPA posteriorly, a mirror image limb will result [34, 35]. Shh not only controls the radial-ulnar and tibial-fibular patterning, but also dictates digit number and identity [36, 37].

Fig. 1.6 Scanning electron micrograph of neural tube and paraxial mesoderm that has begun to segment into somites (from cranial to caudal). Reprinted with permission from Weinstein SL, Flynn JM. Lovell and Winter's Pediatric Orthopaedics. 7th ed. Philadelphia, PA: Lippincott, Williams & Wilkins. 2014; p. 5

Dorsal-ventral axis development is regulated by another set of signals derived from both mesodermal and ectodermal tissues. Several signaling proteins, including *engrailed* (EN-1) and *Wnt-7a* interact to control expression of *LMX-1*, a homeobox gene encoding a transcription factor that acts to dorsalize mesoderm [38, 39].

Genes involved in limb patterning are often important in the development of more than one axis. For example, Shh is required for normal proximal–distal outgrowth and Wnt-7a expression is necessary for normal anterior–posterior patterning [40, 41]. Combinatorial expression of patterning genes that determine limb axes has the downstream effect of activating various members of the HOX A and HOX D families of genes [42]. *HOX* genes are expressed in an overlapping fashion, such that variations in pattern induce the

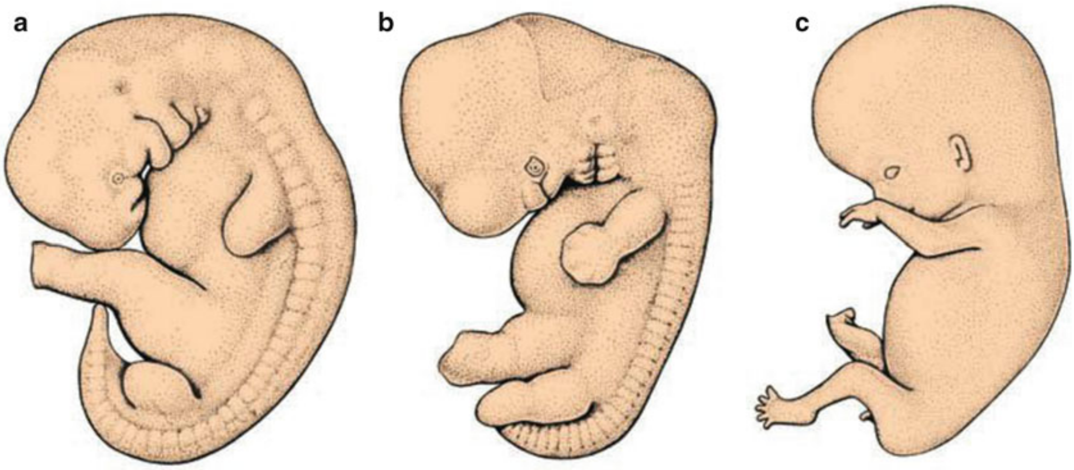


Fig. 1.7 Development of limb buds in human embryos: (**a**) 5 weeks, (**b**) 6 weeks, (**c**) 8 weeks. Lower limb development lags behind the upper limb by 1–2 days. Reprinted with permission from Sadler TW. Langman's Medical Embryology. 11 ed. Baltimore, MD: Lippincott Williams & Wilkins. 2010; p. 134

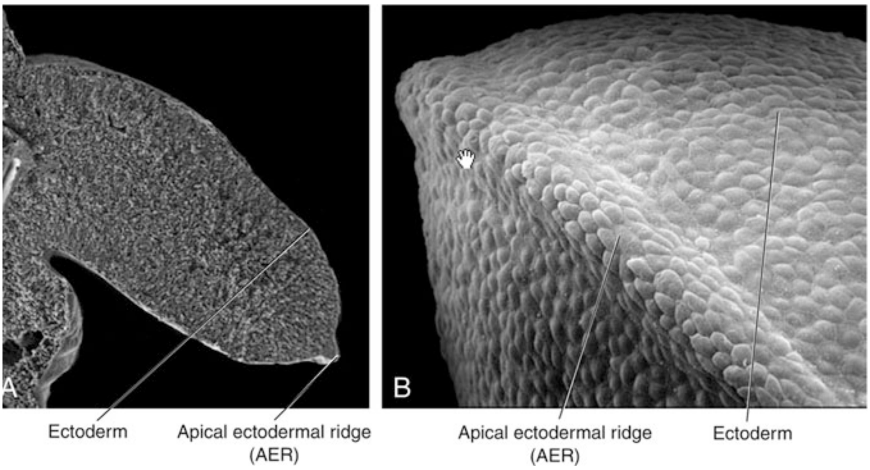


Fig. 1.8 (**a**) Limb bud of a chick embryo, sectioned longitudinally to expose a mesenchymal core covered by a layer of ectoderm. Distally the ectoderm thickens into the apical ectodermal ridge (AER). (**b**) External view of the surface of a limb bud AER. Reprinted with permission from Sadler TW. Langman's Medical Embryology. 11 ed. Baltimore, MD: Lippincott Williams & Wilkins. 2010; p. 135

formation of different limb elements, such as the different skeletal structures in the forelimb versus the hindlimb (Fig. 1.9).

Limb Deficiencies, Malformations, and Teratogens

Given the complex and orchestrated events involved in limb development, it is no wonder that the limbs are commonly involved when congenital anomalies are present. Major structural anomalies are present in 2–3 % of live-born infants and represent the leading cause of infant mortality, accounting for 20 % of infant deaths [43]. Numerous gene mutations, chromosomal abnormalities, and environmental factors can adversely affect limb development, and anomalies in the limbs may serve as clues for more serious underlying defects. Limb deficiencies occur in 3–8 per 1000 live births, with half occurring as isolated defects and half with other associated malformations [44].

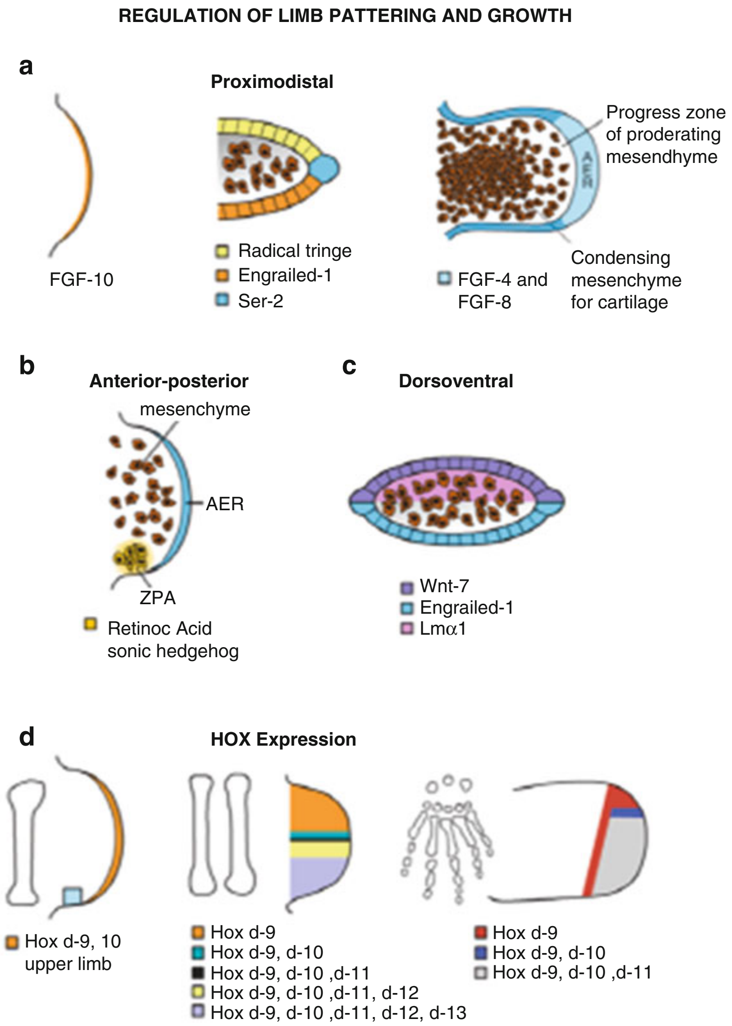


Fig. 1.9 Signaling molecules involved in the regulation of limb patterning and growth. (**a**) Proximodistal outgrowth of the limb bud is initiated by fibroblast growth factors (FGFs) in the lateral plate mesoderm. Once outgrowth begins, the apical ectodermal ridge forms and is positioned at the limb tip by the expression of the gene Radical fringe in the dorsal ectoderm. The AER expresses FGF-4 and FGF-8 to induce the cells of the progress zone to proliferate. (**b**) Anteroposterior patterning is directed by cells in the zone of polarizing activity. These cells secrete retinoic acid, which initiates expression of sonic hedgehog. (**c**) Dorsoventral patterning is controlled by expression of the *WNT7a* gene in the dorsal ectoderm. (**d**) Combinatorial expression of wnt, sonic hedgehog, and FGFs controls activation of various *HOX* genes, whose pattern induces formation of the different limb skeletal elements. Reprinted with permission from Sadler TW. Langman's Medical Embryology. 11 ed. Baltimore, MD: Lippincott Williams & Wilkins. 2010; p. 138

Fetal Period

The period of development from the ninth week to birth is known as the fetal period. It is during this time that tissues and organ systems mature, accompanied by rapid growth in the size of the fetus. By the 12th week, *primary ossification centers* are present in the long bones and skull. During the fourth and fifth months, the fetus lengthens rapidly (such that the relative contribution of the head to overall body length becomes much less). Weight increases occur later in fetal life, particularly during the last 2.5 months, when 50 % of the full-term weight is added [2].

Skeletal Development

Early in limb bud outgrowth, groups of mesenchymal cells begin to organize into pre-cartilage condensations that serve as the template for developing bones (Fig. 1.10). The mesenchymal cells present in the condensations undergo chondrogenesis (differentiation into chondrocytes) and begin to synthesize a cartilaginous extracellular matrix [45]. Molecular control of this process is not fully understood, though it is known that the Hox family of transcription factors play a role in determining the size and shape of the cartilage condensations, at least in part through their regulation of *bone morphogenic protein* (BMP) expression [46]. BMP in turn has effects on the expression of the *Sox* family of transcription factors, which are critical in the differentiation of cartilaginous condensations to chondrocytes and in the elaboration of cartilage extracellular matrix proteins, including *collagen II* and *aggrecan*. Mutations in Sox9 in humans have been shown to lead to campomelic dysplasia, a severe skeletal dysplasia that is often lethal in infancy [47].

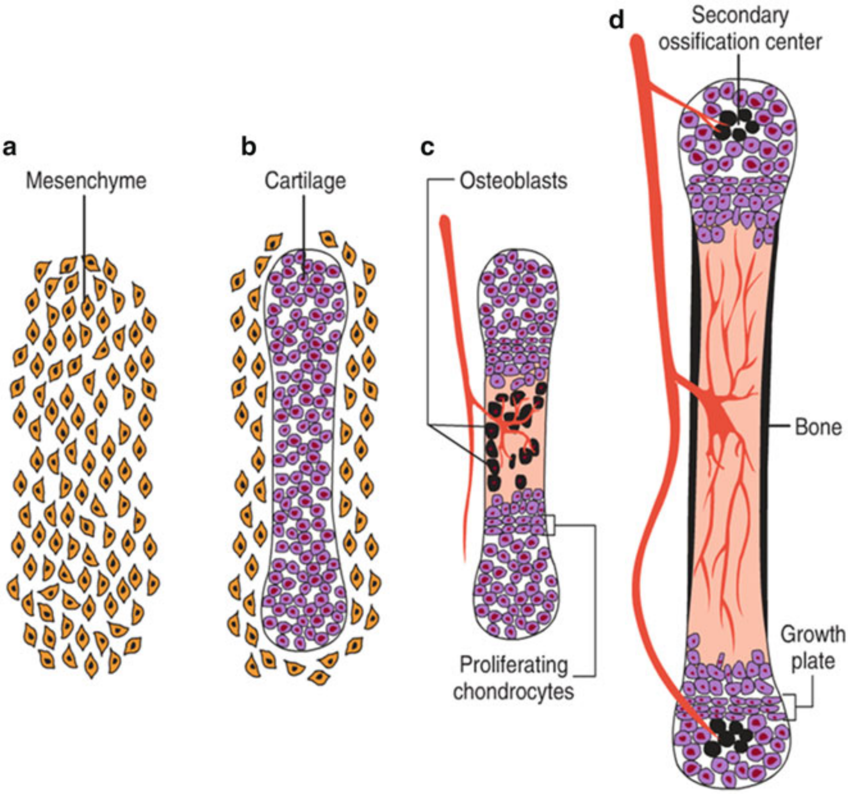


Fig. 1.10 Bone formation. (**a**) Mesenchymal cell condensation. (**b**) After differentiation into chondrocytes, the cells of the condensation form a cartilaginous model of the developing bone. (**c**, **d**) Blood vessels invade, bringing osteoblasts and restricting proliferating chondrocytes to the epiphyses of the bone. When blood vessels invade the epiphyses, secondary ossification centers form. Growth plates are established between the metaphyses and epiphyses of long bones. Reprinted with permission from Sadler TW. Langman's Medical Embryology. 11 ed. Baltimore, MD: Lippincott Williams & Wilkins. 2010; p. 137

Ossification

The cartilage anlage of the skeleton is converted to bone through endochondral ossification. This process is responsible for the formation of the majority of the bone mass in the body, however, the flat bones, such as the calvaria and clavicle, are formed without the presence of a cartilage template through intramembranous ossification.

Intramembranous Ossification

The process of intramembranous ossification involves the direct conversion of neural crest-derived mesenchymal cells into osteoblasts and supportive vascular structures through the interaction with extracellular matrix secreted by the epithelium [48]. The molecular mechanisms involved in the process are poorly understood, but BMPs are thought to play a role. The osteoblastic cells secrete an osteoid matrix, which becomes mineralized directly to bone.

Endochondral Ossification

Beginning during the seventh week of development, chondrocytes at the center of the limb cartilage condensations begin to hypertrophy by increasing their intracellular volume. They secrete an extracellular matrix that is rapidly mineralized and invaded by capillaries from the periphery. The hypertrophic chondrocytes undergo apoptosis and the calcified cartilage matrix begins to degrade, allowing osteoblasts carried in by new vessels to take up residence in the space left behind. These new osteoblasts secrete bony matrix onto the calcified cartilage surfaces, creating mixed spicules of calcified cartilage and bone termed *primary spongiosa*. Subsequent remodeling removes the remaining mineralized cartilage, creating the *secondary spongiosa* and *lamellar bone*. Ossification progresses from the primary center toward the ends of the long bone while concurrent appositional growth is taking place through an intramembranous process that increases bone width.

At the epiphyses of the long bones these same cellular processes are repeated in the secondary centers of ossification. The secondary centers expand radially to convert the whole chondroepiphysis to bone, with the exception of the hyaline cartilage that makes up the adjacent joint surface.

Growth Plate Anatomy

As the shaft and epiphyses progressively ossify, the intervening growth plate cartilage is reduced to a narrow band between the metaphysis and epiphysis of the growing bone. The growth plate, or *physis*, has a structure based on the series of events that occur during endochondral ossification, with anatomic zones distinguished by the unique morphology and biochemical processes occurring at the multiple stages of cartilage differentiation and conversion to bone. The growth plate contains not only the physeal cartilage (which can be further subdivided into *germinal/reserve*, *proliferative*, *hypertrophic*, and *provisional calcification* zones), but also specialized circumferential structures termed the *perichondral ring of LaCroix* and the *groove of Ranvier* (Fig. 1.11).

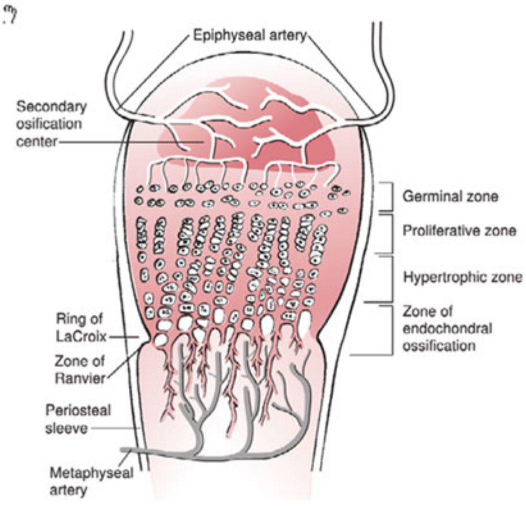


Fig. 1.11 Diagram of the zones of the physis: Germinal, proliferative, hypertrophic, and the Zone of provisional (or endochondral) ossification. The Zone of Ranvier and Periosteal Ring of LaCroix are situated at the junction with the metaphysis as indicated. Reprinted with permission from Rockwood and Wilkins' Fractures in Children 7th Edition. LWW; Seventh edition. 2009; p. 93

Germinal (Reserve) Zone

Cells in the germinal zone exist in a relatively quiescent state. They have a high ratio of extracellular matrix to cell volume, with abundant endoplasmic reticulum for protein synthesis. These cells are thought to be a source of further cells for the proliferative zone.

Proliferative Zone

This zone is characterized by long columns of relatively flattened chondrocytes, oriented along the longitudinal axis of the bone. Oxygen tension is high is this zone, and cells here have the highest rate of extracellular matrix synthesis [49]. The metaphyseal end of the proliferative zone is also termed the "*Zone of Maturation*," in which matrix synthesized by proliferating cells allows them to separate from one another.

Hypertrophic Zone

In the hypertrophic zone, no further cell division takes place, and cells increase their intracellular volume by five to seven times. These cells also increase production of alkaline phosphatase and type X collagen [50]. This zone is the most common zone through which Salter-Harris fractures, or fractures involving the growth plate, occur.

Zone of Provisional Calcification

Also termed the "*Vascular Invasion Zone*," the zone of provisional calcification functions to mineralize the cartilage extracellular matrix between hypertrophic chondrocytes. As the chondrocytes progress through programmed cell death, vascular loops invade the calcified matrix, bringing osteoblasts that begin bone synthesis [51].

Perichondral Ring of LaCroix and Groove of Ranvier

Circumferentially surrounding the growth plate is a fibrous band of tissue that provides mechanical stability to shear, tension, and compressive loads, termed the perichondral ring of the LaCroix [52]. The ring merges with metaphyseal periosteum and provides a covering for the proliferative chondrocyte progenitor cells of the Ranvier groove that contribute to the increase in diameter of the growing bone [47].

Growth Plate Vascularity

The growth plate itself is an avascular structure that relies on diffusion for the delivery of nutrients and oxygen to the metabolically active chondrocytes in the proliferative and hypertrophic zones. Three different vascular systems contribute to the blood supply of the growth plate, including the *epiphyseal arteries*, *metaphyseal vascular channels*, and *perichondral arteries*. Prior to skeletal maturity, the epiphyseal arteries are the only blood supply to the epiphysis, and branches of these vessels pass through the resting zone and supply the uppermost proliferative zone cells of the physis. Vascular channels within the metaphysis eventually contribute to the majority of the growth plate blood supply. *Vascular endothelial growth factor* (VEGF), which is secreted by hypertrophic chondrocytes, directs the invasion of a longitudinally oriented capillary network into the provisionally calcified zone [51]. Perichondral arteries are also present that supply the groove of Ranvier and perichondral ring of LaCroix.

Synovial Joints

The synovial joints develop from early limb cartilage condensations when chondrogenesis halts and areas of high cell density, called *interzones*, form through poorly understood signal cascades [53]. Cell death is induced, and cavitation of the space between opposing skeletal elements ensues. Cells surrounding the new joint differentiate into articular cartilage, synovium, and the joint capsule.

Normal and Abnormal Growth

An understanding of growth in the child is central to the diagnosis and management of nearly all pediatric orthopedic conditions. Growth contributes not only to changes in size and shape of skeletal elements, but it also influences both pathologic processes affecting the bones and soft tissues and the ability of the body to heal and adapt after insult. As described above, growth results from a highly ordered sequence of cellular and extracellular events, converting undifferentiated mesenchymal tissue into the various skeletal elements. The consequence of these changes at the macroscopic level is one of increasing height and weight, as well as changing body proportions [54]. In the growing child, it is these macroscopic changes that we can see and measure clinically, and that provide us with a reference for assessing normal and abnormal growth states.

General Growth Concepts

Growth occurs most rapidly during the fourth month in-utero, when femoral length is increasing by an average of almost 1 cm per month [55–58]. By the end of the second trimester, the fetus reaches 70 % of its final predelivery length, but has achieved only 20 % of its final birth weight. Weight increases most rapidly over the third trimester, while growth velocity slows. Despite relative decreases in growth velocity following the fourth month of gestation, by the time of a child's birth, growth is still proceeding at a very rapid pace. Height gain in the first year is of the same magnitude as that gained during all of puberty [54]. The growth rate continues to slow until age 4 or 5 years, when a steady state is reached, which persists until the pubertal growth spurt. Between ages 5 and 10 years, height increases approximately 5 cm per year.

Not only is growth velocity non-uniform during childhood, but the rate of growth within each body segment is variable and ever-changing. At birth, the infant's head makes up 25 % of standing height, which decreases to 13 % at maturity. Conversely, the lower limbs make up 30 % of standing height at birth, but 48 % at skeletal maturity (Fig. 1.12) [54]. The relative contributions of the limbs and spinal segments to growth can be monitored with sub-ischial and sitting heights, respectively. During the first 5 years of life, sitting height and sub-ischial length increase at nearly equal amounts. From 5 years to the onset of puberty, sub-ischial length contributes two-thirds of the height gain with sitting height contributing one-third. From onset of puberty to maturity, this ratio is reversed, with sitting height having a greater contribution [59]. These differential contributions of the body segments to growth have important clinical consequences, as the time remaining for lower limb growth is relatively limited following the onset of puberty. For procedures relying on limb growth such as epiphysiodesis and hemiepiphysiodesis, timing of the procedure must be adjusted to take this into account.

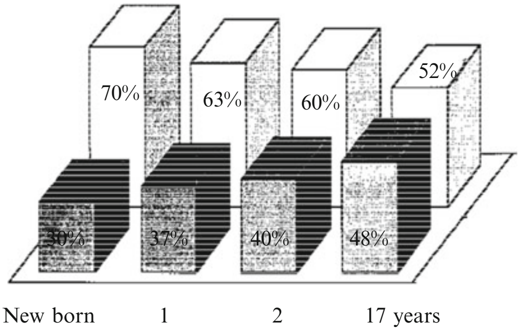


Fig. 1.12 Proportion in percentage of total height attributed to the lower limb (*dark bars*) and sitting height (*white bars*) at different stages of development. Reprinted with permission from Dimeglio A. Growth in pediatric orthopaedics. J Pediatr Orthop. Jul-Aug 2001;21(4): 549–555

Puberty

Following the age of 10 years, patterns of growth in girls and boys diverge somewhat. The pubertal growth spurt begins at approximately 13 years of (skeletal) age in boys and 11 years of age in females. Changes in stature, as well as in overall body proportions, morphology, and sexual characteristics, define the pubertal period. Growth velocity increases rapidly, with a peak occurring approximately 2 years after the onset of pubertal changes; at this point girls will grow 8 cm/year and boys 9 cm/year [60–63]. Increases in limb growth velocity occur early, such that after age 13 in girls and 15 in boys, little growth in the lower limb takes place. What remaining growth occurs after this point comes almost exclusively from increases in sitting height [64, 65]. Determination of the timing of the period of most rapid growth, or *peak height velocity* (PHV) is of the utmost importance, as conditions that are affected by growth (e.g. scoliosis) may worsen significantly around this time.

Maturity Assessment

Individual differences in activation of the hypothalamic–pituitary–adrenal and hypothalamic–pituitary–gonadal axes as well as environmental factors and body composition lead to variation in the exact timing and duration of the pubertal period, thus making predictions about the timing of growth and of PHV based on chronologic age somewhat difficult. The most accurate assessment of peak height velocity is with sequential, closely spaced, height measurements. Given the logistical requirements needed for multiple measurements, however, indirect measures of maturity (both clinical and radiographic) are frequently employed to predict the timing of peak growth.

Secondary sexual characteristics as described by the *Tanner stages* include stages of pubic hair development as well as breast development in girls and penile/scrotal development in boys [66]. These stages can be used for determination of accelerated growth, as girls typically reach PHV by Tanner stage 2–3, and boys by Tanner stage 3–5. Menarche is another readily identifiable indicator of maturity in girls, though it typically occurs after PHV, and thus is of limited utility clinically.

Skeletal age, based on the radiographic changes that occur in the growing skeleton, is generally a more accurate and useful tool for maturity measurement than clinical findings, particularly once children enter puberty [67]. Moreover, Tanner stages can be difficult to ascertain in the typical office setting. Skeletal age determinations have their origin in several epidemiologic studies involving serial radiographs of "normal" children over time both in the United States and Europe. Radiographs were compiled into atlases with representative radiographs displayed for a wide range of ages. One of the more commonly used of these, the *Greulich and Pyle Atlas* [68], utilizes hand radiographs for determination of bone age. A more efficient Shorthand Bone Age assessment method was also recently developed, which was derived from the Greulich and Pyle atlas, but requires only a single drawing or table and not the entire atlas itself. Other methods of maturity assessment utilize radiographs of different growing bones, such as the Tanner-Whitehouse (hand and wrist), Sauvegrain (elbow), and Oxford (hip and pelvis). All have shown good efficacy in skeletal age determination and have been used clinically [69–72]. Notably, studies have shown that up to 50 % of children have a skeletal age that differed from their chronologic age by >6 months [54].

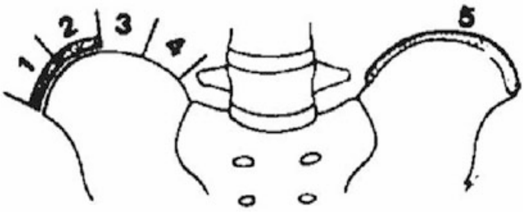


Fig. 1.13 The Risser sign. Based on iliac apophyseal ossification, note that ossification proceeds in lateral to medial direction. Reprinted with permission from Weinstein SL, Flynn JM. Lovell and Winter's Pediatric Orthopaedics. 7th ed. Philadelphia, PA: Lippincott, Williams & Wilkins. 2014; p. 31

The *Risser sign*, based on development of the iliac apophysis, is another commonly used method of skeletal maturation determination, as it is assessable on spine radiographs obtained in the evaluation of scoliosis (Fig. 1.13) [73–75]. The iliac apophysis typically does not begin to ossify (Risser 1) until after the PHV, and its appearance marks the beginning of the descending slope of pubertal growth velocity. Progressive ossification of the apophysis proceeds in an orderly fashion during part of the growth spurt and by Risser III, there is typically 1 year of growth remaining. Dimeglio suggests using the Risser sign in conjunction with the state of the triradiate cartilage, greater trochanteric apophysis, and olecranon apophysis for a more accurate assessment of maturation [54].

Lower Limb Growth

The various body segments do not grow at the same magnitude or rate, and often their peak growth velocities are not temporally related. Lower limb growth is rapid in the first 5 years, steady throughout childhood, and has a less-pronounced peak during the pubertal growth spurt.

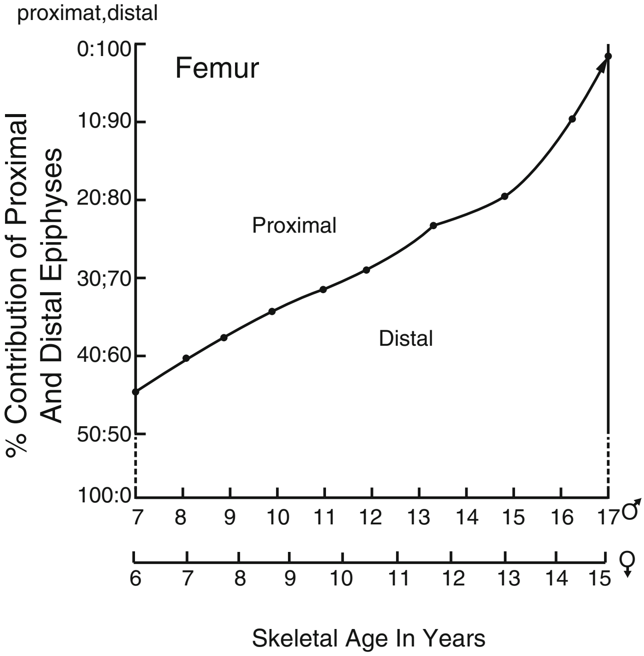


Fig. 1.14 Relative contribution of proximal and distal femoral growth plates at different ages. Reprinted with permission from Pritchett JW. Longitudinal growth and growth-plate activity in the lower extremity. Clin Orthop Rel Res. 1992;275: 274–9

Femur-Specific Growth

The femur accounts for 55 % of the growth of the lower extremity, and maintains a constant relative length to the tibia that is established by early childhood. The proximal and distal growth centers do not contribute equally to growth, with the proportion changing over time. Overall, about 70 % of femoral growth comes from the distal physis, but in girls, the contribution is 60 % at 7 years of age and 90 % at age 14. This pattern is similar in boys, with 55 % of femoral growth distally at 7 years and 90 % by age 16 (Fig. 1.14) [76]. Variability in growth at each physis has implications both in the use of epiphysiodesis for growth modulation, and in prediction of leg length inequality in the setting of growth arrest. For example, growth arrest in the proximal femoral physis from trauma would have a much more significant effect on a child prior to the pubertal growth spurt than thereafter, even if overall growth of the limb at the two times was not significantly different. Historical methods of growth prediction often used average or "rule of thumb" growth rates from the respective femoral and tibial physes for use in determination of timing of epiphysiodesis in leg length discrepancy. In one study, these methods led to a over- or under-correction rate of up to 50 % [77].

Abnormal Growth and Limb-Length Discrepancy (LLD)

Limb-length discrepancy is a common sequelae of fracture involving the femur, and can result from growth acceleration or retardation, shortening or angulation at the fracture site, and treatment-related alteration of growth at the proximal or distal femoral physes. Whether fracture-related limb length differences require treatment depends on their magnitude, associated deformity, patient-specific expectations, and treating physician experience. Discrepancies less than 2 cm have been shown to have little effect on gait, and thus observation, with or without use of a shoe-lift insert in the heel as needed for the improved comfort of the child, is usually recommended for differences of this magnitude [78–81]. With larger discrepancies, however, more invasive treatment may be indicated, ranging from more substantial orthotics to growth modulation, lengthening, or shortening of the limb, depending on the degree of discrepancy predicted at maturity. Subtle, asymptomatic limb length differences are a common clinical finding even in the uninjured general population, with more than one-third of healthy military recruits found to have a >0.5 cm discrepancy [82].

Growth Acceleration

While long bone overgrowth after fracture is a well-recognized phenomenon, the mechanism remains somewhat poorly understood. It has been suggested that hyperemia and increased vascularity related to fracture healing may induce the physis of the injured bone to increase its rate of growth [83]. Other evidence suggests that hormonal influences may be at play [84]. Recent animal studies indicate that the overgrowth may be related to chondrocyte proliferation at the physis as a result of local biological processes, though not increased vascularity [85, 86]. The ipsilateral tibia is often seen to overgrow as well, albeit to a lesser degree. Reports of the average expected overgrowth occurring after fracture of the femur vary from 0.6 to 1.1 cm, but with ranges from 0 to 2.5 cm or more [87–98]. There is much disagreement regarding the factors associated with overgrowth, with authors variably reporting fracture location, gender, handedness, age, and degree of angulation or shortening to affect the amount of subsequent length increase. It is generally accepted that overgrowth occurs most rapidly in the first 18 months to 2 years following a fracture, and decreases thereafter. Overgrowth is most common in children ages 2–10 years.

Shortening and Angular Deformity

Given the above discussion, in non-operatively treated femur fractures, some shortening at the fracture can be well tolerated (or even preferable), with the expectation that overgrowth of around 1 cm is likely to occur. In the 2- to 10-year-old patient, shortening of the fracture up to 2 cm or so is acceptable.

Some degree of angular deformity is also common after femoral fractures in children, particularly those in young children treated closed with Pavlik harness (less than 9 months of age) or spica casting (less than 5 years of age). Deformities in this age group remodel to a great degree with growth, both from appositional bone formation at the fracture site and through asymmetric growth at the physis. Guidelines for acceptable deformity vary widely, and depend on patient age and the plane of the deformity. In young children (<2 years), up to 40° of anterior/posterior angulation may be acceptable. This decreases to 10° or less in older children and adolescents. Acceptable Varus/valgus angulation similarly decreases as a child ages, with varus angulation (10–15° in infants, 5–10° in older children) being generally less well tolerated than valgus (20–30° in infants, 10° in older children) [99–101]. Deformity associated with fractures around the knee is less well compensated for than fractures of the shaft, and tolerable limits are stricter [101]. Angular deformities may contribute to leg length inequality, and in some cases may cause a significant enough discrepancy to require treatment.

Physeal Injury

Unique to pediatric orthopedics is the presence of the physis in growing bones, a structure susceptible to injury from forces that would otherwise produce fractures of the metaphysis or articular surface in adults [102–106]. Fractures of the physis are commonly described by the classification of Salter and Harris (Fig. 1.15) [107]. As depicted in Fig. 1.11, the hypertrophic and zones of provisional calcification are primarily apoptotic cells and vascular channels, and are thus structurally weaker than the other portions of the physis. Salter-Harris type I and II fractures therefore tend to pass through these two layers. Salter-Harris type III and IV fractures pass through all zones of the physis and have a higher likelihood of growth disturbance. However, this is, in some ways, an over-simplified view of how traumatic injuries affect the physis, as microscopic studies have shown complex planes of injury involving all four layers of the physis, even in Salter-Harris type I fracture patterns [103, 108–110].

General management principles for fractures involving the physis involve gentle reduction, through either open or closed means, of the physeal

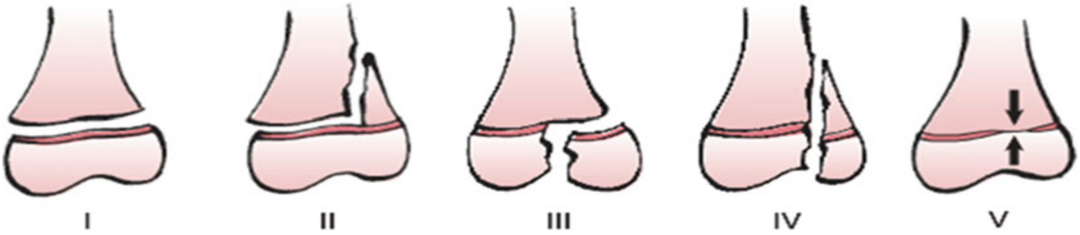


Fig. 1.15 Salter-Harris classification of fractures. In type I fractures, the fracture line extends through the physis, often with no radiographically apparent abnormality at the time of injury. In type II fractures the fracture line extends across the physis and exits the metaphysis. In type III fractures, the fracture line crosses the epiphysis from the articular surface and exits the physis. In type IV fractures the fracture line traverses epiphysis, physis, and exits the metaphysis. Type V fractures represent a crush injury to the physis. Reprinted with permission from Rockwood and Wilkins' Fractures in Children 7th Edition. LWW; Seventh edition. 2009; p. 99

fragments such that the layers of the physis are restored to as anatomically correct a position as possible. This is particularly true to Salter-Harris type IV fractures, in which the fracture line crosses both metaphysis and epiphysis. Direct visualization of the physeal reduction is recommended, as displacement of these fracture fragments without an anatomic or optimized reduction can lead to metaphyseal–epiphyseal bar formation and growth disturbance [111]. Associated fractures to the articular surface must also be anatomically reduced so as to minimize the risk of later degenerative changes.

Clinical and Radiographic Evaluation of Growth Disturbance and LLD

Important in the evaluation of any child with a congenital or acquired limb length difference is a careful history to elucidate any syndromic conditions or relevant history of trauma, infection, or malignancy. Examination should include sitting and standing height measurements, as well as individual measurements of the length and circumference of the extremities. Leveling the pelvis in stance using blocks is a reliable method for measuring overall limb length difference. Supine evaluation with the Galeazzi test for femur length (relative knee height with patient supine and hips flexed to 90°) and prone inspection of tibial length (with knees flexed) can give segment-specific measurements. Careful inspection for skin markings is necessary, as characteristic skin findings may be present in the setting of many congenital causes of LLD such as vascular malformations or neurofibromatosis. Finally, all joints should be clinically evaluated for the presence of contractures or abnormal motion. Flexion contractures at the hip or knee can alter radiographic measurements of leg length and be problematic if not recognized.

Quantitation of limb length discrepancy or growth disturbance can be made through a number of different imaging modalities, with the choice of study largely dependent on patient age, location of discrepancy/deformity, and etiology. A scanogram image consists of a series of images taken at the hip, knee, and ankle, superimposed over a ruler beside both extremities. A standing hips-to-ankles X-ray allows for evaluation of coronal angular deformity as well as length discrepancy (Fig. 1.16a–c). CT scanogram can be helpful in the setting of concurrent hip or knee flexion contracture. MRI and ultrasonography can be used when radiographic landmarks are not present (as with very young children), and have the advantage of no radiation exposure.

Growth Prediction

In children with normal growth of the extremities, and in those with limb length discrepancies, prediction of growth is often clinically useful. A number of methods for growth prediction in the lower extremities have been developed, many of which are based on Green and Anderson's cross-sectional studies investigating growth of the extremities. In their initial work, radiographs from over 800 individuals were used to develop

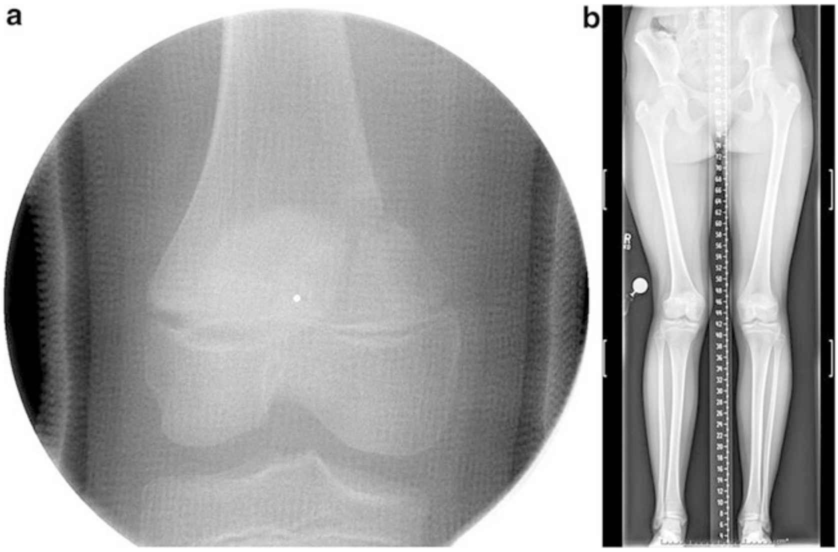


Fig. 1.16 (**a**) AP radiograph of the distal femur of a 10-year-old girl who suffered a Salter-Harris type II distal femur facture. This was managed conservatively in a long leg cast. (**b**) Hips-to-ankles AP radiograph of same child 3 years later, showing significant leg-length difference related to physeal arrest after her fracture

norms for limb length from 5 years to skeletal maturity [112]. Later studies by the authors refined growth-remaining curves such that predictions could be made regarding the effect that epiphysiodesis would have on the length of the limb based on skeletal or chronologic age [113, 114]. Serial measurements of a child's limb lengths allowed for plotting on the Green and Anderson nomograms for both long and short limbs, such that the difference at maturity could be calculated and timing of intervention to alter growth could be determined. The arithmetic method initially proposed by White [115] used Green and Anderson data to approximate distal femoral growth at 3/8 in. (10 mm) per year and proximal tibial growth at 1/4 in. (6 mm) per year. In this method, girls are assumed to reach skeletal maturity at age 14 years and boys at age 16 years. An estimate of appropriate timing for epiphysiodesis can then be made. Other methods utilizing the same longitudinal data have been developed in an attempt to simplify and improve the accuracy of growth prediction.

Moseley [116, 117] developed nomograms from adjusted Green and Anderson data, such that limb lengths could be plotted and standard reference slopes following epiphysiodesis of various limb segments could be used to determine timing of epiphysiodesis to equalize limb lengths at maturity (Fig. 1.17). The Multiplier method is another useful application of historical growth data [118–120]. From the Green and Anderson studies, tables of multiplier values were determined such that limb length inequality at maturity could be predicted from the discrepancy at any age times the multiplier for that age.

Treatment of Leg-Length Discrepancy, Angular Deformity, and Growth Arrest

While a comprehensive review of treatment for lower limb deformity is beyond the scope of this chapter, general principles of management of these complex issues bear highlighting.

Leg-Length Discrepancy

Important in the treatment of limb length issues is a discussion with the patient about goals of care, as physician and patient expectations may differ significantly. A previously outlined framework for expectations is trying to achieve a leg length discrepancy less than 2 cm at maturity, relatively equal knee heights, a level pelvis, and an efficient gait pattern [78, 121]. For discrepancies of less than 2 cm, intervention is rarely indicated, but a

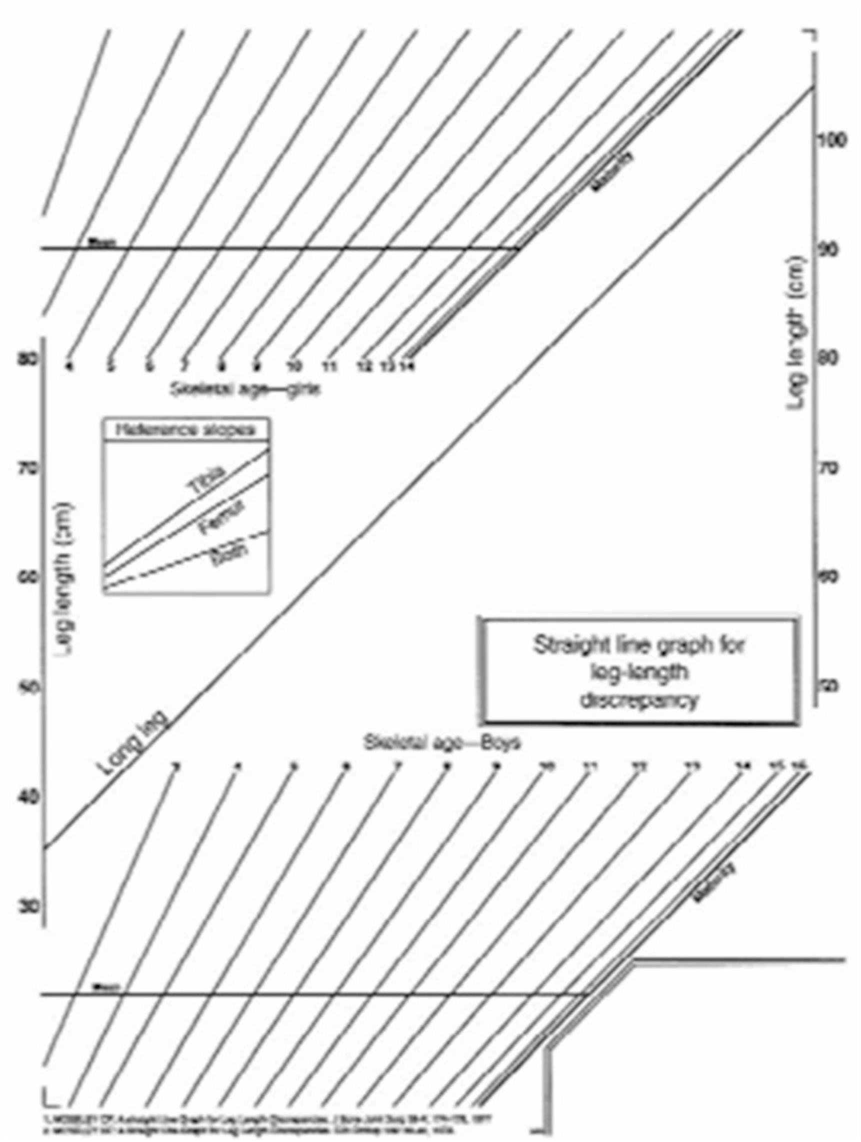


Fig. 1.17 Straight line graph developed by Moseley for determination of leg-length discrepancy at maturity based on limb length measurements at two or more timepoints. Reprinted with permission from Journal of Bone and Joint Surgery American, 1977, 59, 2, A straight-line graph for leg-length discrepancies, Moseley, 174–179

shoe lift can be used if the patient is symptomatic. Discrepancies predicted to be 2–6 cm in magnitude can be managed in a number of ways, including shoe lifts, surgical shortening, lengthening of the short limb or, most commonly, epiphysiodesis of the long limb. If deformity is present, correction of deformity in conjunction with a lengthening procedure is an attractive option. For larger differences, 6–20 cm discrepancy predicted at maturity, one or more lengthening procedures should be considered. Discrepancies greater than 20 cm are generally treated with prosthetic fitting, often with surgical augmentation of the limb with lengthening or amputation. “Heroic lengthening” procedures for discrepancies of this magnitude have also been performed, though with significant complication risk.

Angular Deformity

Deformities outside of the acceptable range (see "*Shortening and Angular Deformity*" above) may require treatment. Intervention for angular malalignment after femur fracture should generally be delayed up to a year after healing to determine the remodeling potential of a patient with growth remaining. Options for treatment of angular deformities depend in part on the location of the deformity, the magnitude, and the amount of growth left prior to skeletal maturity. With significant remaining growth, less invasive "guided-growth" techniques may be applicable, including hemiepiphysiodesis by Blount staples (Zimmer; Warsaw, IN), percutaneous epiphysiodesis with transphyseal screws (PETS), or an 8-plate device (eight-Plate; Orthofix, McKinney, TX) (Fig. 1.18a, b) [122–125]. Each of these techniques is designed to slow or arrest growth at the physis on the convex side of the deformity to allow growth of the physis on the concave side of deformity and achieve gradual correction. In older children with insufficient growth remaining, osteotomy can be performed to achieve either acute or gradual correction.

Growth Arrest

Growth plate injury from fracture or iatrogenic causes can result in physeal bar formation and either partial or total growth arrest. Depending on the size and location of the physeal arrest, this can lead to length discrepancy, angular deformity, or both. Prior to treating a growth arrest surgically, advanced three-dimensional imaging—either CT or MRI—is necessary to outline the extent of the arrest and localize it within the physis (Fig. 1.19). As a general guideline, bridge resections should be limited to those which occupy less than 25–50 % of the growth plate surface area and in those patients who are projected to have an at least 2 cm leg length discrepancy

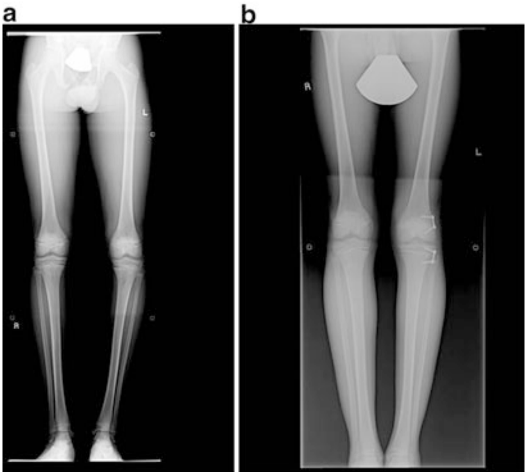


Fig. 1.18 Radiographs showing the use of 8 plates in treating genu varum deformity in a 14-year-old boy. (**a**) Hips-to-ankles AP radiograph at presentation. (**b**) Repeat hips-to-ankles AP radiograph 8 months after 8-plate placement showing resolution of varus deformity

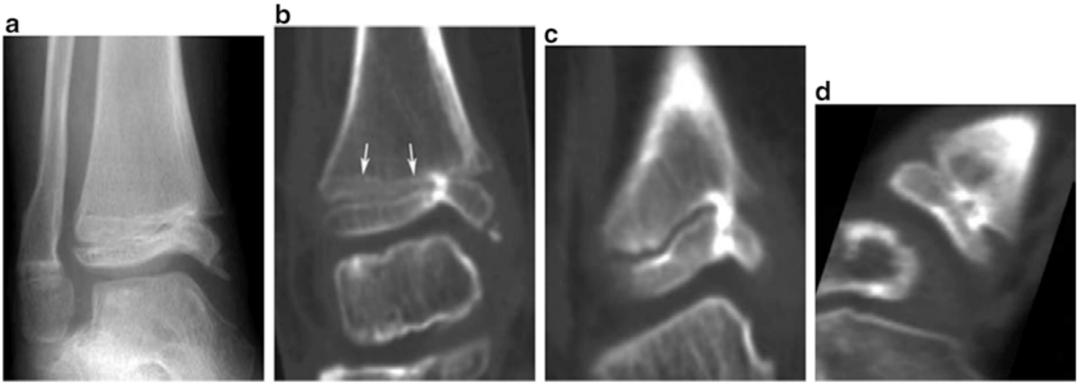


Fig. 1.19 (**a**) Anteroposterior radiograph of the distal tibia demonstrating Harris growth arrest line tapering to the medial distal tibial physis. (**b**) Coronal plane CT image showing physeal bar and growth arrest line. (**c**, **d**) Further CT images showing extent of physeal bar formation. Reprinted with permission from Rockwood and Wilkins' Fractures in Children 7th Edition. LWW Seventh Edition. 2009; p. 109

and at least 2 years of growth remaining [126–129]. In a physeal arrest felt to be appropriate for resection, care must be taken to fully resect bridging bone with minimal trauma to the surrounding healthy physis. Spacer material should then be placed in the cavity formed by the resection. Typically, this material is autogenous fat or methyl methacrylate cement [128, 130]. Radiopaque markers should be implanted at the time of bar resection such that future resumption of growth can be documented.

In the setting where a physeal arrest is not resectable, or where previous arrest resection procedure was unsuccessful, completion epiphysiodesis is a frequently employed strategy. In a patient with significant growth remaining, this has the potential to create a leg length discrepancy, which can then be managed by lengthening the short limb or by epiphysiodesis or shortening of the contralateral extremity.

Anatomy

Bone Development

By the sixth week of fetal development, the first cartilaginous models of the bones of the extremities begin to form, with ossification of the limbs beginning at approximately the seventh week in utero. The primary ossification center of the femur arises in the diaphysis of the bone, and progresses longitudinally toward each end. The secondary center at the proximal end begins as a single chondroepiphysis that later separates to become the capital femoral epiphysis (responsible for growth of the femoral neck) and trochanteric apophysis (responsible for appositional growth of the greater trochanter) [131]. The capital femoral epiphysis begins to ossify by 4 months in girls and 5–6 months in boys, and the trochanteric apophysis ossifies later, at approximately 4 years of age (Fig. 1.20) [132]. The distal femoral epiphysis ossifies just prior to birth, and its presence radiographically can be used as a marker for a full-term infant.

Vascular Anatomy of the Proximal Femur

The unique anatomical arrangement of the developing proximal femur creates a complex network of vessels that supply the proximal epiphysis, and make this area vulnerable to vascular insult from trauma or other causes. The vascular supply to the developing hip has been well studied [133–136], with changes noted as a child ages. Before 4 years of age, blood flow to the femoral head is predominantly from interosseous branches of the lateral and medial femoral circumflex arteries. With growth, the physis becomes more of a barrier to blood flow, and the intracapsular branches of the medial femoral circumflex artery (posterosuperior and posteroinferior retinacular vessels) predominate (Fig. 1.21) [137]. The artery of the

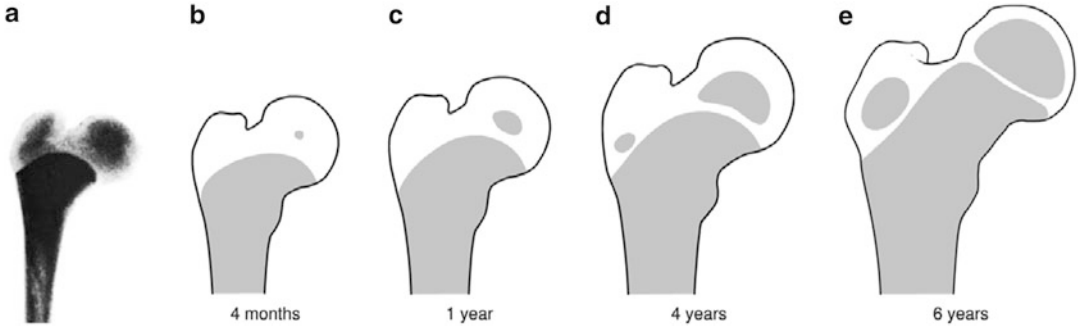


Fig. 1.20 Transformation of confluent proximal femoral chondroepiphysis into separate growth zones of femoral head and greater trochanter. (**a**) Radiograph from stillborn fetus. (**b**–**e**) Drawing based off of radiographs of the proximal femur at various developmental timepoints. Reprinted with permission from Edgren W. Coxa plana. A clinical and radiological investigation with particular reference to the importance of the metaphyseal changes for the final shape of the proximal part of the femur. Acta Orthop Scand Suppl. 1965:Suppl 84:81–129

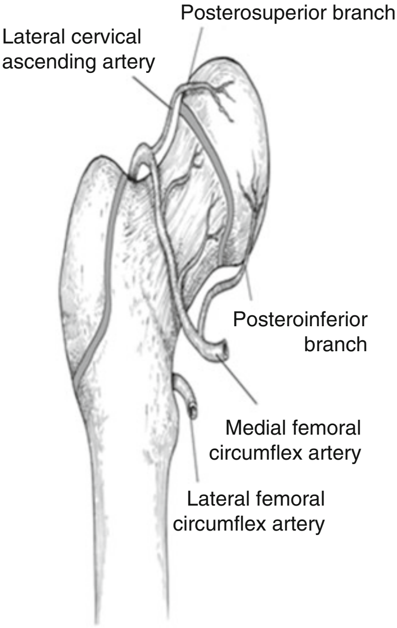


Fig. 1.21 Posterior view of the vascular supply to the proximal femur. Reprinted from Beaty J. Fractures of the Hip in Children. Orthop Clin North Am. 37:223–32; copyright © 2006, with permission from Elsevier

ligamentum teres does not contribute significantly to the blood flow of the femoral head until age 8–10, and even then contributes only a small proportion (up to 20 %) of the total.

Distal Femoral Physis

The physis at the distal end of the femur is particularly susceptible to growth disturbance after fracture, regardless of Salter-Harris type or quality of reduction. It is positioned proximal to the attachments of the collateral ligaments, and varus or valgus stresses that in a skeletally mature individual might lead to ligament failure, instead lead to tensile failure through the growth plate [138]. In children less than 2 years, the physis has a relatively flat shape, however, with growth it becomes more undulating and irregular. The changes in morphology create more intrinsic stability, however, fractures through an undulating physis may disrupt multiple regions and contribute to the high rate of growth arrest [139, 140].

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2

Radiologic Evaluation of Femur Fractures

Carley Vuillermin and Sarah D. Bixby

Overview of Imaging Modalities

Radiographs

Plain radiographs are the first-line imaging modality for patients with suspected femoral fracture and are usually the only imaging modality needed for both diagnosis and treatment. Standard radiographic views of the femur include images in orthogonal projections, typically anteroposterior (AP) and lateral radiographs. Initial radiographs not only identify fractures, but also may suggest the presence of underlying pathologic lesions that may have predisposed the patient to fracture. The entire femur, including the hip and knee joints, should be imaged with orthogonal views. Disruptions to joints above and below the fracture with dislocation or subluxation are more common with certain fracture patterns and have implications for recommendations regarding further imaging. Scrutiny of the soft tissues for foreign body or soft tissue gas is also important, as these signs may indicate an open injury or a soft tissue infection. Proper patient positioning is also important to evaluate for the degree of overriding of the fracture fragments, and the extent of fracture displacement and angulation. Specific types of radiographs will depend on the location of the fracture, and will be discussed in detail later on in the chapter.

Computed Tomography (CT)

Computed tomography (CT) of the femur may be helpful for pre-operative planning for surgery on complex femoral fractures, or to further evaluate a possible pathologic lesion. Radiation doses will vary based on patient girth, field of view, tube current, image thickness, and amount of overlap between slices, among other factors. Each of these factors may be adjusted to minimize radiation dose. In general, lower-dose imaging protocols are the norm rather than the exception in pediatric imaging. In musculoskeletal imaging in particular, CT dose may be reduced significantly without sacrificing image quality, particularly when the indication for imaging is fracture. With current multi-detector row CT (MDCT) technology, thin-section axial datasets can be acquired quickly, with sub-millimeter slice thickness and spacing. These thin sections allow the data to be reformatted into other planes without additional radiation exposure. Reformatted images are often more helpful than axial data because the femur is

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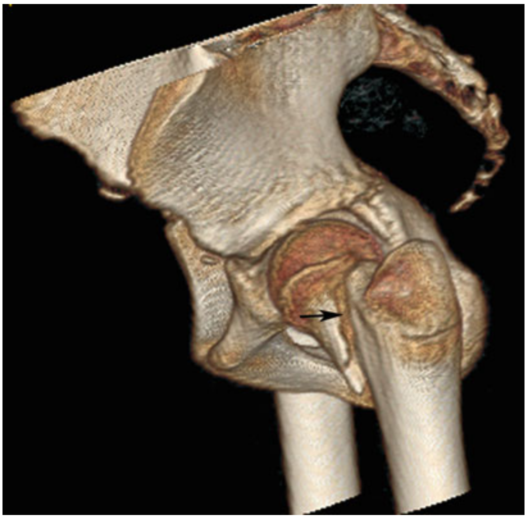


Fig. 2.1 3D reconstructed CT image of the pelvis using bone algorithm in an 11-year-old female s/p MVA demonstrates a left femoral neck fracture (*black arrow*) with mild posterior displacement of the femoral shaft with respect to the neck

projected in coronal and sagittal planes, which are comparable to radiographic views. MDCT with reformats accurately assess the degree of angulation and displacement of a femoral fracture in the coronal, sagittal, and transverse planes. The data may be used to create three-dimensional reconstructions of the fracture (Fig. 2.1), and may further identify and characterize a pathologic lesion (Fig. 2.2). CT does not require the use of intravenous contrast to evaluate the bony structures, but contrast may be necessary when there is concern for a vascular injury.

Magnetic Resonance Imaging (MRI)

Indications for performing MRI of the femur depend on the type and location of fracture, and the risk of fracture complications. Magnet strengths vary by institution, though most imaging systems are 1.5 or 3.0 T. Dedicated extremity magnets with lower field strength magnets exist, though the hip and femur are not easily positioned within an extremity-only magnet. Higher field strength magnets are often preferred due to improved image resolution and decreased imaging time relative to lower field strength systems. Coil selection and patient positioning in the coil are determined by the location of the fracture. Review of prior radiographs, if available, is critical for selecting the correct imaging coil and field of view for the examination. An MRI may require anywhere between 20 and 60 min of imaging time. Repeating sequences due to improper coil position or field of view selection may have a deleterious impact on the patient's ability to remain still, in addition to further delays for subsequent patients. Fractures of the proximal femur may be imaged with a surface coil placed over the affected hip, or a body/torso coil over the pelvis. Fractures involving the distal metaphysis or peri-physeal region, on the other hand, may be better evaluated using a dedicated knee coil. Though imaging protocols will vary depending on the specific indication for imaging, most protocols include fluid- and cartilage-sensitive sequences, as well as T1-weighted images to evaluate bone marrow signal. Fluid-sensitive sequences are often performed with fat suppression, which allows marrow and soft tissue edema to appear more conspicuous against the suppressed fat. T2-weighted sequences are fluid-sensitive and are often performed with chemical fat suppression. Cartilage-sensitive sequences include proton-density weighted sequences as well as gradient

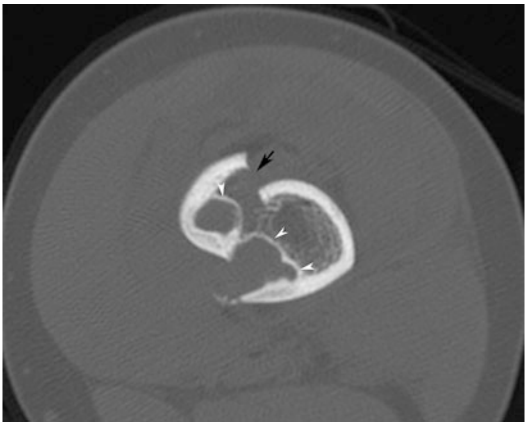


Fig. 2.2 Axial image from a noncontrast CT scan of the femur in an 11-year-old boy demonstrates a fracture (*black arrow*) through a cortically based lesion with well-defined, sclerotic margins (*white arrowheads*), which represented a non-ossifying fibroma (NOF)

echo sequences. Standard gradient echo sequences often have faster acquisition times compared to traditional spin-echo (e.g. T1, T2, Proton Density) sequences. There are also a variety of isotropic, thin-section, volumetric gradient echo sequences available today that allow for detailed evaluation of cartilage surfaces. Intravenous contrast may be required in cases of suspected avascular necrosis or infection, or if a pathologic lesion is suspected on prior imaging.

Ultrasound

Ultrasound is rarely indicated in patients with femur fractures. One notable exception is preterm neonates and infants with suspected physeal injuries and/or epiphyseal separations. The distal femoral epiphysis normally ossifies around 38 weeks' gestation, and the proximal femoral ossification center ossifies at around 4 months of age. In extremely young infants it may not be possible to detect the location of the femoral ossification center using radiographs. In these patients, ultrasound may be very helpful in imaging the cartilaginous epiphyses and detecting periosteal elevation and epiphyseal separation [1]. Specific findings of these injuries at ultrasound will be discussed further on the section on imaging young infants.

Fracture Imaging Based on Location

Imaging of femoral trauma usually is directed by initial clinical assessment and mechanism of injury. Plain radiographs should focus on the primary region of interest, though it is also important to exclude associated injuries, including other fractures within the same bone, adjacent, or contralateral extremities [2]. Indications for advanced imaging modalities will be discussed in relation to imaging specific fracture types, as well as the section outlining the management of potential complications. In significantly displaced fractures, initial treatment should not be delayed pending advanced imaging where the additional imaging is unlikely to change the primary management, and delay in treatment may compromise outcome.

Proximal Femoral Fractures, Radiographic Evaluation, and AP Pelvis

Most fractures involving the proximal 1/3 of the femur will be diagnosed on the AP pelvis radiograph; this is part of a standard trauma imaging series. It is important not to use gonadal shielding as this may obscure key radiographic information. Ideally the limb will be in an approximate anatomic alignment in order to make interpretation more accurate; however, forceful movements should be avoided due to the risk of causing additional injury or causing significant discomfort to the patient. Assessment should be systematic, including both the bone and soft tissue elements. Cortical integrity should be assessed as well as the trabecular pattern. Subtle changes in trabecular orientation may be indicative of incomplete fractures. Shenton's line should be a smooth arc being created by the inferior aspect of the superior pubic ramus and the inferior aspect of the femoral neck. The femoral head should be concentric to the acetabulum. In small children this is hard to assess, as much of the acetabulum is a cartilage anlage, however it should be symmetric with the contralateral side. Small intra-articular gas bubbles may be seen on plain X-ray after a traumatic femoral head dislocation and subsequent reduction, however these are more readily appreciated on CT (Fig. 2.3). Soft tissue assessment includes evaluating for foreign material, calcifications, or gas indicative of possible open injuries. At times soft tissue creases can be mistaken for fracture lines, however they will extend beyond the cortical margins of the bone. Many fractures are readily diagnosed if there is a clear cortical disruption with either translation or angulation.

The AP pelvis radiograph changes significantly as a child matures and secondary centers of ossification appear and subsequently fuse (see Table 2.1 and Table 2.2). Skeletal maturity, in

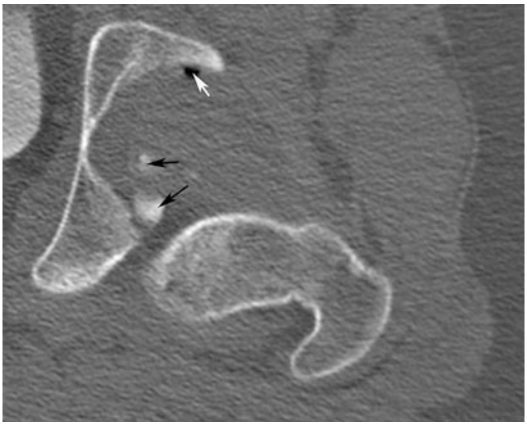


Fig. 2.3 Axial CT image through the left hip from a CT of the abdomen and pelvis in an 18-year-old female s/p high speed MVA demonstrates posterior dislocation of the femur with at least two posterior acetabular wall fracture fragments projecting in the joint space (*black arrows*) and a small focus of gas within the joint (*white arrow*). This patient required surgical reduction of the hip with open reduction and fixation of the posterior wall fracture fragments

Table 2.1 Normal timing of appearance of ossification centers [4]

Ossific nucleus	Age of ossification
Femoral head	4 months
Greater trochanter	3 years
Lesser trochanter	11–12 years

Table 2.2 Normal timing of fusion of physes [3]

Physis	Age at closure (years)
Triradiate cartilage	12–14
Proximal femur	16–18
Greater trochanter	16–17
Lesser trochanter	16–17

particular the state of the physes, is critical in assisting selection of definitive management (Fig. 2.4a–c).

Cross-Table Lateral

Once an intra-capsular fracture of the femoral neck has been diagnosed, it is important not to move the limb and risk disrupting the retinacular blood supply any further. Cross-table (shoot-through) lateral radiographs of the femur can be performed without moving the affected leg. This is a cross-table view with the beam angled 45° to the table. The beam is centered on the femoral head or region of interest. This view can also be utilized for extra-capsular proximal femoral injuries. Once a bone is fractured then the proximal fragment will not necessarily move with distal limb repositioning, thereby limiting the information gained with the frog lateral. Limiting movement also minimizes the pain experienced by the child.

Frog-Leg Lateral

In trauma the frog lateral is predominantly reserved for instances where no fracture has been seen on the AP radiograph and orthogonal views are needed to further assess the region and exclude fracture. This may be somewhat limited in the hip given that the greater trochanter may project over the femoral neck in an area of concern (Fig. 2.5a, b). The hip is flexed 30–40° and abducted 45°, bringing the proximal femur into lateral profile with an AP beam orientation. This view is not useful for additional characterization of acetabular pathology.

Radiographic Classifications of Proximal Femoral Fractures

Fracture Dislocations

Fracture dislocations of the proximal femur and hip joint are radiographically classified according to the Stewart Milford classification (Fig. 2.6) [5, 7]. Unlike in the adult these injuries are uncommonly associated with acetabular fractures [5]. Imaging in these fracture patterns is aimed at ensuring that the hip joint is reduced and that the reduction is concentric. Intra-articular fragments need to be specifically looked for and are best imaged via CT (Fig. 2.7). The size, location, and displacement of acetabular or femoral head fragments must be assessed (Fig. 2.8). The findings will dictate the manage-

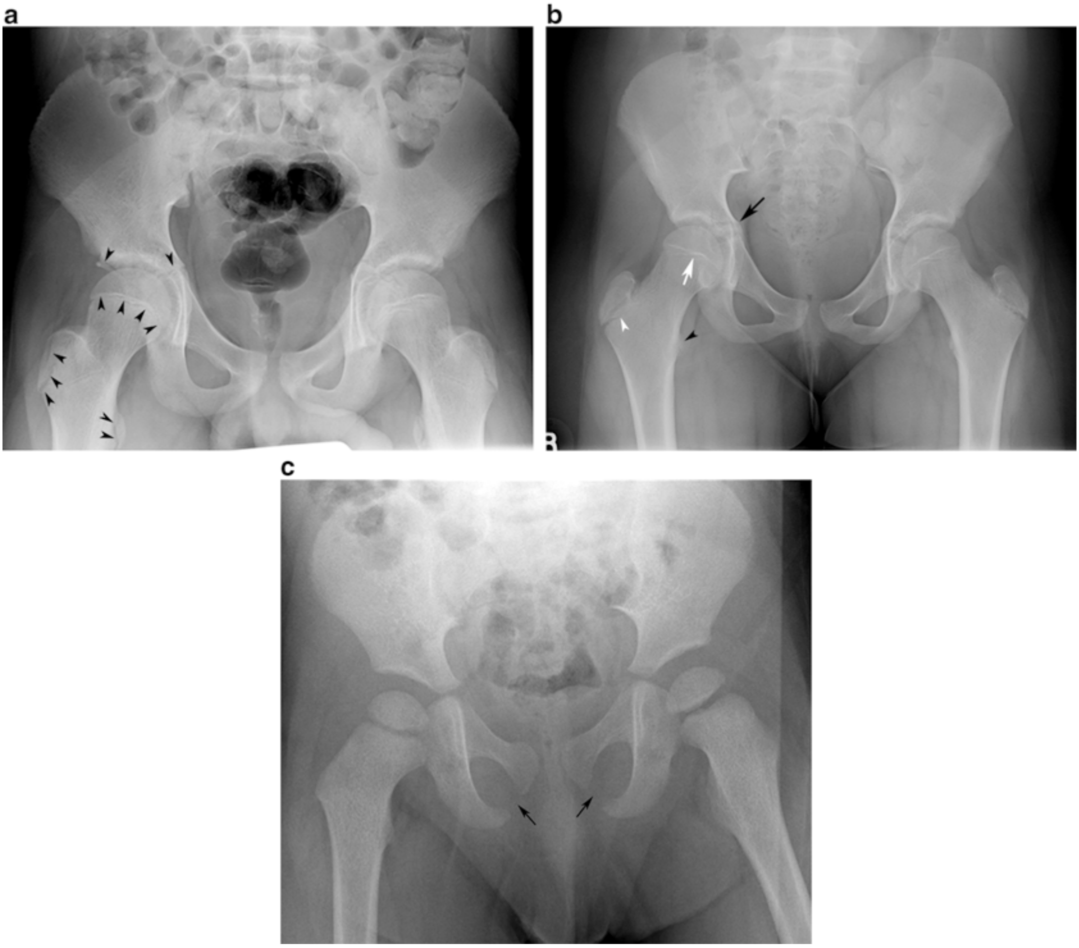


Fig. 2.4 (**a**) AP radiograph of the pelvis in a 13-year-old male after car accident, demonstrates normal appearance of the open physes of the femoral heads, greater and lesser trochanters, triradiate cartilage, and acetabula (*black arrows*). This child sustained no pelvic or femoral fractures. (**b**) AP radiograph of the pelvis in a 10-year-old female demonstrates the normal appearance of the triradiate cartilage (*black arrow*), proximal femoral physes (*white arrow*), greater trochanter (*white arrowhead*), and lesser trochanter (*black arrowhead*). (**c**) AP radiograph of the pelvis in a 20-month-old male after trauma demonstrates the normal appearance of the open physes of the pelvis and femur. Note the appearance of the unfused synchondroses (*black arrows*)

ment, including the operative approach. Femoral head fractures are classified according to the Pipkin Classification of femoral head fractures [8] (Fig. 2.9). It is important to remember that in children the osseous component may only represent a small proportion of the total fragment. Cross-sectional imaging is also essential as a standard post-reduction step to confirm concentric reduction and the absence of intra-articular fragments, with MRI having the advantage of elucidating size and position of chondral fragments (Fig. 2.10a–c) [6].

Femoral neck fractures are classified according to the radiographic classification of Delbet [9] (Fig. 2.11). In pediatric hip fractures this has been shown to be prognostic, especially in the development of AVN [10]. If suspicion arises for possible intra-articular fragments, including widening of the joint space without fragment visible, or an acetabular rim fracture or femoral head fracture is seen on plain radiographs, then patients should undergo CT scanning. CT is the preferred imaging modality as it is better at characterizing the size and location of bony fragments. If clini-

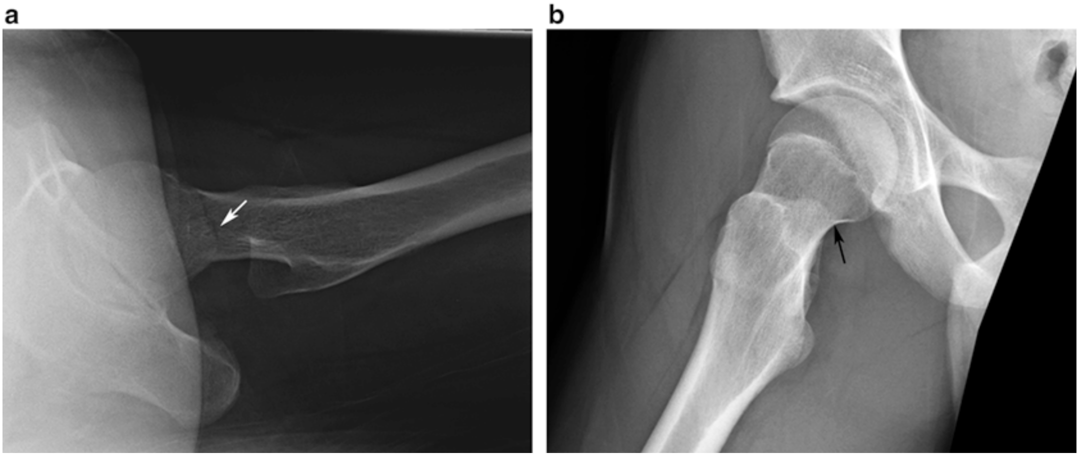


Fig. 2.5 (**a**) Cross-table lateral radiograph of the left femur in a 15-year-old female s/p fall demonstrates a fracture through the femoral neck (*white arrow*). (**b**) Frog-leg lateral radiograph of the right hip in a 15-year-old male with a stress fracture through the inferomedial femoral neck (*black arrow*) partially obscured by the overlying greater trochanter

cal suspicion remains for a fracture of the proximal femur and plain radiographs are negative, then MRI is the imaging modality of choice. MRI has been shown to be more sensitive than CT in detecting nondisplaced femoral neck fractures [11] (Fig. 2.12a, b). It can also be utilized for imaging possible physeal separations in younger children, where a chondral lesion may be contributing to a failure of concentric reduction following dislocation, or for assessing the size of a posterior wall fragment in fracture dislocations [12]. Femoral neck fractures are characterized by the location of the fracture within the neck, including subcapital (Fig. 2.13), transcervical (Fig. 2.14), cervicotrochaneric, and pertrochanteric (Fig. 2.15a, b).

Physeal Fractures

Physeal fractures of the proximal femur are less frequent than distal femoral physeal injuries. The most common physeal injury of the proximal femur is slipped capital femoral epiphysis (SCFE). Although trauma may be part of the presentation in SCFE, it is generally considered a primary hip condition rather than a femur fracture, as there are other factors in addition to trauma that predispose patients to SCFE including obesity and endocrine disorders, as well as the shape of the acetabulum [13]. SCFE is most often diagnosed on the basis of pelvic radiographs. Traumatic epiphyseal separation of the proximal femur is a rare injury that may occur after high-impact trauma, such as a fall from a height or a high-speed motor vehicle collision. The femoral head is often completely dislocated from the acetabulum. These fractures are diagnosed on the basis of radiographs, and CT imaging with 3D reconstructions may be performed to better define the spatial relationship between the femoral head, neck, and acetabulum. These fractures are catastrophic injuries with a high rate of avascular necrosis (>80 %) even after treatment [14] (Fig. 2.16a, b).

Femoral Shaft

AP and Lateral Femoral Radiographs

For suspected formal shaft fractures, initial views of the femur are obtained with the limb in approximate anatomic alignment. Ideally the entire femur will be imaged on a single radiographic plate (Fig. 2.17). Standard radiographic plates are up to 14 in. × 17 in. Placing the plate obliquely will increase the available length (Fig. 2.18). Consideration may be given to using a long plate (3 ft, stitched film) or it may be necessary to use two separate radiographs to ensure that the entire

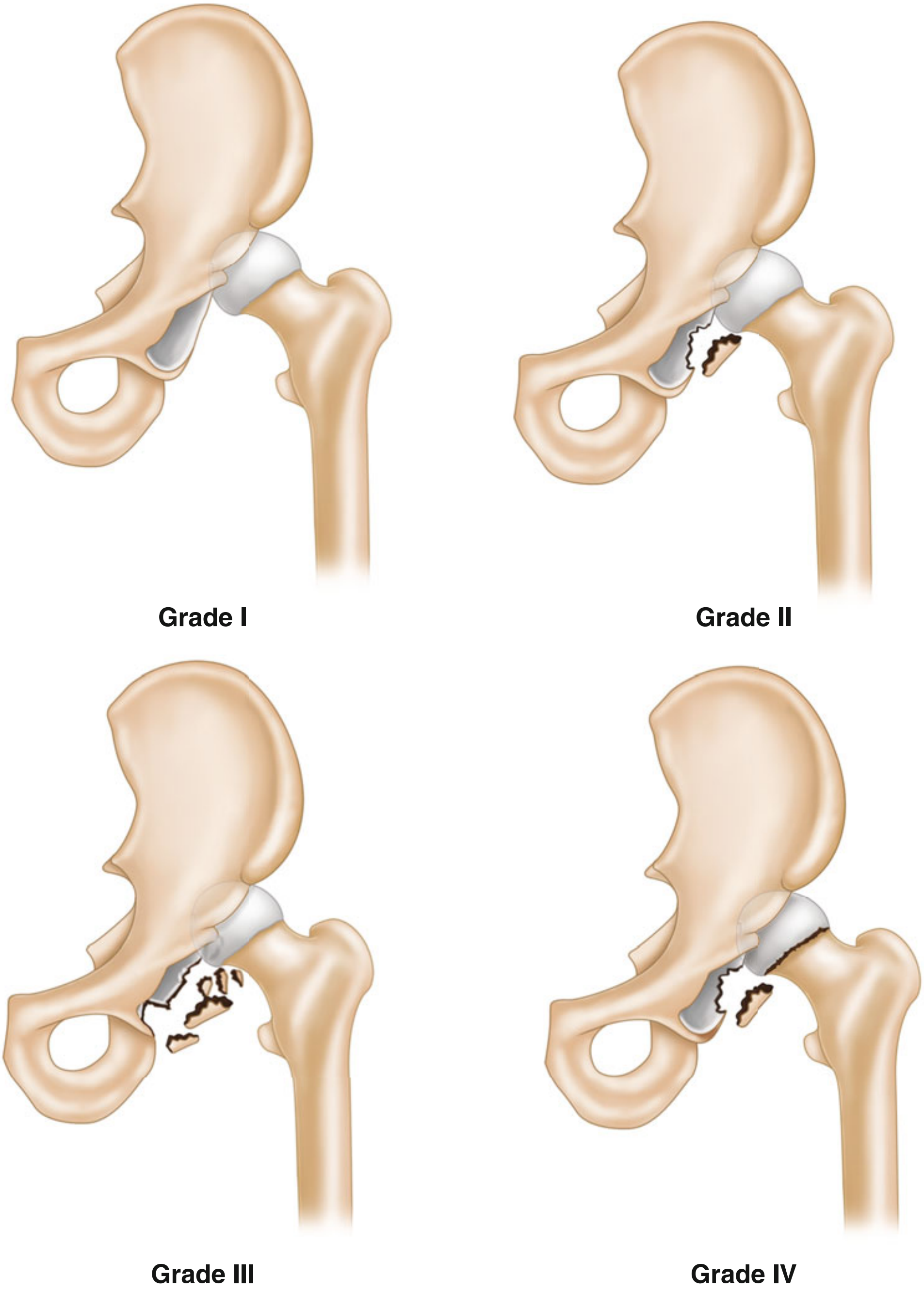


Fig. 2.6 Illustration demonstrating the Stewart Milford classification of hip fracture/dislocations

femur, including the joints above and below, are imaged. Assessment of the film should include the fracture pattern, classified according to the AO classification (Fig. 2.19). Specific features to note include the degree of displacement and angulation, the anatomic location (either proximal, middle or distal third of the diaphysis), the inner canal diameter on both the AP and lateral

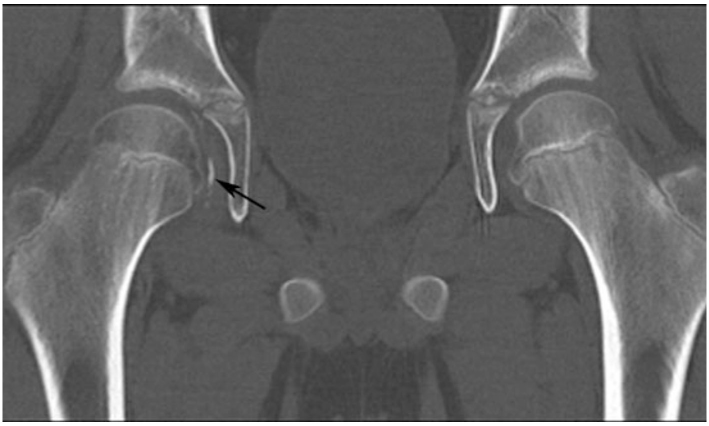


Fig. 2.7 Coronal reformatted image from a noncontrast CT scan of the pelvis in a 12-year-old male s/p ski injury with a crescentic fragment projecting in the right hip joint inferior to the fovea (*black arrow*), which represented an avulsed fragment from the femoral head (Pipkin type 1 fracture)

Fig. 2.8 Coronal reformatted CT image through the left hip in a 18-year-old female s/p high-speed MVA demonstrates Grade III fracture/dislocation injury according to Steward Milford classification. There is widening of the medial joint space secondary to two posterior acetabular wall fracture fragments projecting in the joint space (*black arrows*) and a nondisplaced fracture through the medial wall of the acetabulum (*black arrowhead*). This required surgical dislocation for removal of the loose bodies

radiographs, and the skeletal maturity of the patient. In addition, it is important to assess the soft tissues to look for defects, gas, or foreign material (Fig. 2.20). Each of these factors will assist in management decision-making.

Associated Injuries

Femoral shaft fractures are predominantly high-energy injuries. They are associated with ipsilateral proximal [2, 15] and distal femoral fractures, dislocations of adjacent joints, ligamentous and meniscal injuries of the knee [16], as well as proximal tibial [17] and pelvic fractures. In general, management of long bone fractures should not be delayed pending MR scanning to assess soft tissue injuries, especially in the setting of vascular injury.

Distal Femoral Fractures

Physeal Fractures

Fractures of the distal femoral growth plate are common in children, as the physeal cartilage is weaker than surrounding bones and ligaments. The physis is involved in 15–30 % of all long bone fractures in children [18]. The most widely used classification scheme for growth plate fractures is the Salter-Harris classification system, which is based on the extent of involvement of the physis, metaphysis, and epiphysis [19] (Fig. 2.21). Salter 2 is the most common type of physeal fracture [20–22] and consists of a fracture through both the physeal plate and the metaphysis. The metaphyseal fragment may be easily detected if there is significant displacement of the fragment, though these fractures may be subtle on radiographs if little to no displacement has occurred (Fig. 2.22a, b). Salter 3 and Salter 4 fracture through the femoral condyles are rare injuries, usually related to a high-energy traumatic event [23]. These fractures extend to the articular surface of the femoral condyle, a finding that may be subtle on radiographs but

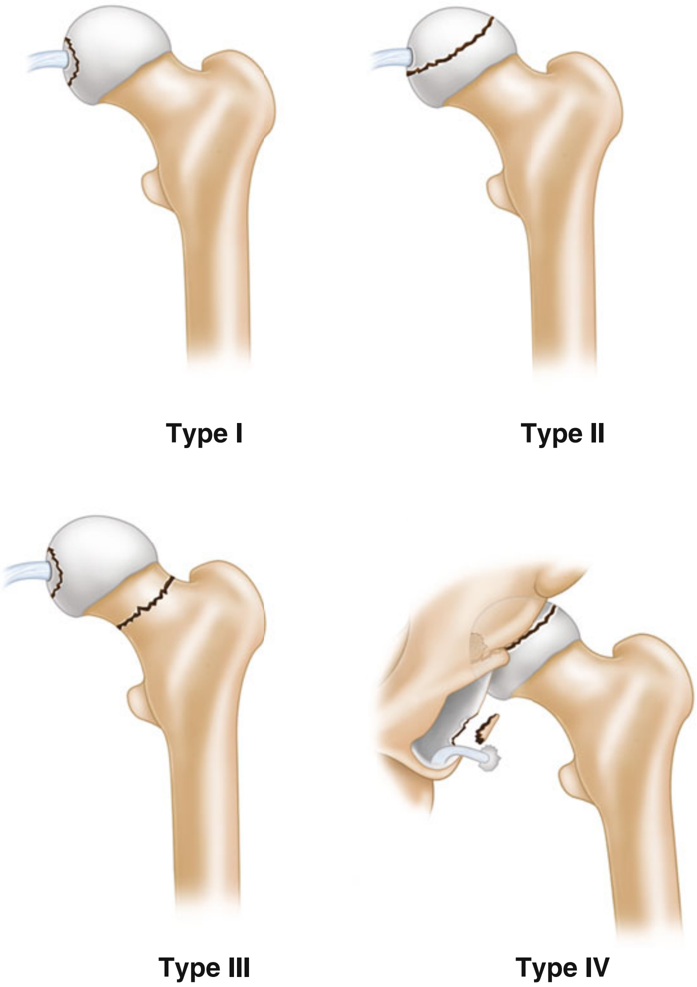


Fig. 2.9 Pipkin classification of femoral head fractures

well depicted with CT. CT is also helpful for identifying "Hoffa fractures," the coronal plane fracture within the lateral femoral condyle. Initial radiographic classification of a fracture is often modified after MRI [24] when subtle epiphyseal or metaphyseal fracture lines are detected. For these reasons, it is not uncommon for a patient with a known or suspected fracture in the region of the distal femoral physis to undergo further cross-sectional imaging (Fig. 2.23a, b).

Systematic review of any MRI of the knee in a patient with a traumatic injury and equivocal or negative radiographic findings should include scrutinizing the physes for widening, epiphyseal or metaphyseal fracture lines, bone marrow edema, and periosteal elevation [25]. Additional advantages of MRI in evaluating fractures around the physis include the ability to evaluate for additional internal derangement of the knee, including cruciate or collateral ligament injuries, chondral injuries, and meniscal tears. MRI in patients with known or suspected distal femoral physeal injury may be performed with a dedicated knee coil. Standard T1, PD, and T2-weighted spin-echo sequences are usually sufficient to identify and characterize the fracture (Fig. 2.24a, b). Images should be acquired in all three imaging planes (axial, coronal, and sagittal) to fully characterize the fracture in each plane. With modern imaging sequences this may be performed with one volumetric, 3D sequence, ideally with proton density weighting which can be reformatted into different

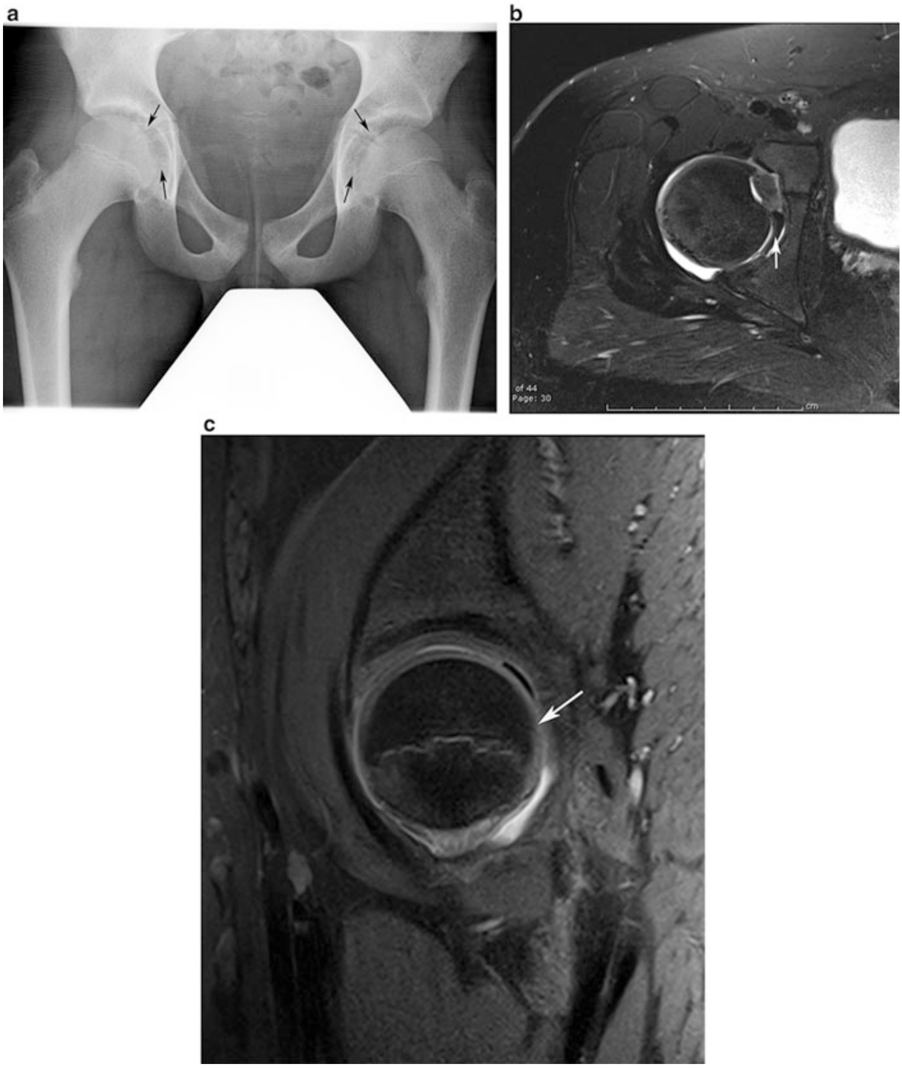
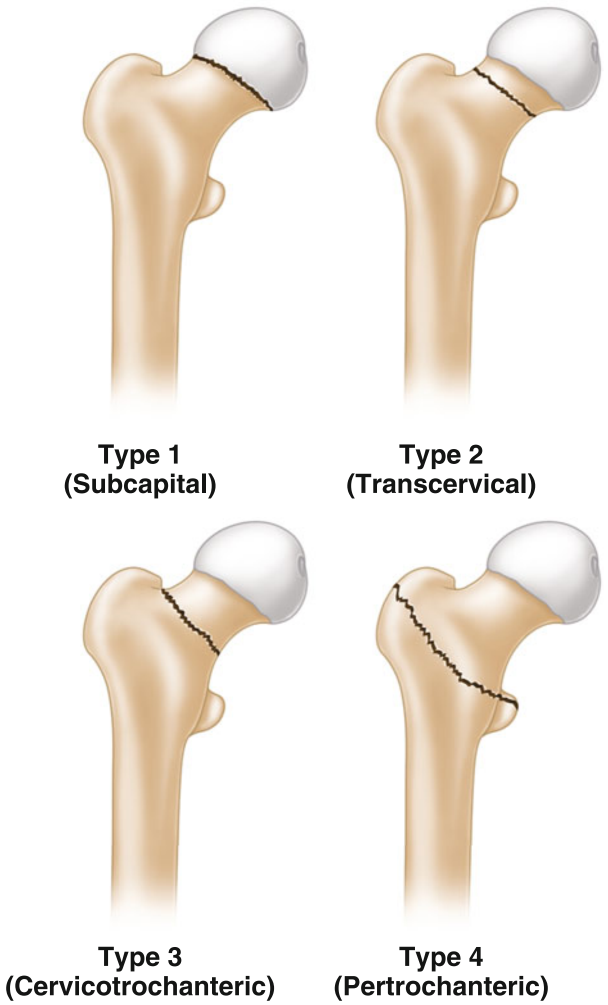


Fig. 2.10 (**a**) AP radiograph of the pelvis in a 15-year-old male s/p MVA demonstrates relative widening of the left hip joint space compared to the right (*black arrows*) consistent with nonconcentric reduction. Subsequent MRI revealed entrapment of the posterior labrum within the central joint space on the left side. (**b**) Axial T2-weighted image with fat suppression in a different 12-year-old male after hip dislocation/relocation demonstrates a flipped posterior labrum in the joint space (*white arrow*). The ligamentum teres has also avulsed from the femoral head. (**c**) Sagittal proton density-weighted image with fat suppression in a 12-year-old male after hip dislocation/relocation demonstrates a flipped posterior labrum in the joint space (*white arrow*)

planes. One T1-weighted sequence (most often in the coronal plane) is preferred for evaluating the marrow signal and demonstrating linear, low-signal intensity fracture lines. T2-weighted images with fat suppression reveal the surrounding marrow edema and fluid signal within the involved portions of the physis. On fluid-sensitive sequences, the physis should appear as a band of bright signal between the low signal intensity epiphyseal plate and zone of provisional calcification [18] (Fig. 2.25). Interruption of the physis manifests as an area of low signal intensity within the physis on fat-suppressed water-sensitive sequences [18] (Fig. 2.26). It is not uncommon to see small “tongues” of physeal cartilage extending into the metaphysis after a Salter-Harris



Type 1 (Subcapital)

Type 2 (Transcervical)

Type 3 (Cervicotrochanteric)

Type 4 (Pertrochanteric)

Fig. 2.11 Illustration demonstrating the Delbet classification of femoral neck fractures

injury. These physeal cartilage irregularities are likely related to a traumatic vascular insult [26], but are not usually associated with growth disturbance. Disruption of the periosteum may also be detected at MRI. When periosteal stripping or disruption is detected at MRI, careful attention should be given to the periphery of the physis to ensure that the stripped periosteum is not entrapped within the physis (Fig. 2.27).

Subarticular Fractures

The term “bone bruise” is often used to describe an area of marrow edema (bright signal on fat-suppressed, fluid-sensitive sequences) in patients with a known trauma history. A traumatic impaction injury may lead to various types of subcortical contusions and fractures depending on the precise mechanism. Vellet et al. described five subcortical fracture patterns, all of which demonstrated decreased T1-weighted signal and increased T2-weighted signal on MRI images [27]. Most of these injuries are occult on radiographs. Reticular fractures are areas of reticular stranding and signal abnormality within the marrow distant from the cortical bone. Geographic fractures are contiguous with the cortical bone. Linear fractures are discrete, linear areas of signal abnormality usually less than 2 mm wide (Fig. 2.28). Impaction fractures occur in conjunction with geographic or reticular fractures, and demonstrate variable

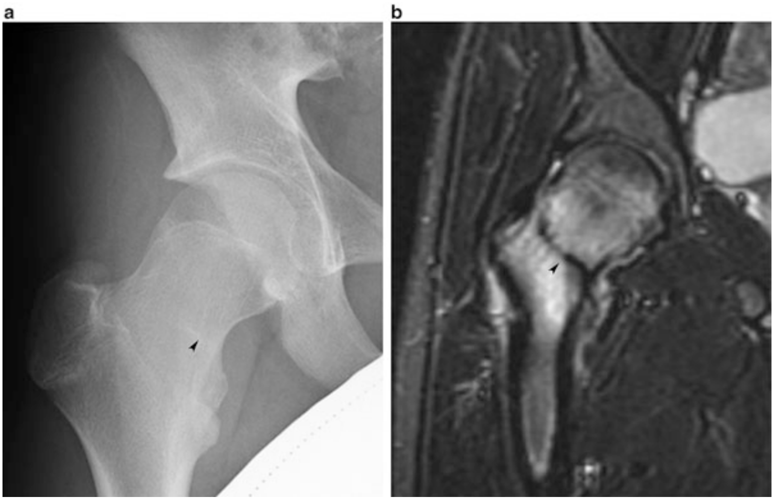


Fig. 2.12 (**a**) AP radiograph of the right hip in a 15-year-old cross-country runner with right hip pain demonstrates a subtle, thin, linear sclerotic band along the inferior femoral neck perpendicular to the trabecular markings (*black arrowhead*). (**b**) Coronal T2-weighted image fat-suppressed image of the right hip in the same 15-year-old male runner demonstrates a dark linear fracture line at the inferior margin of the right femoral neck which is perpendicular to the trabecular markings (*black arrowhead*), with surrounding marrow edema

Fig. 2.13 Frog-leg lateral radiograph of the left femur in a 20-month-old male s/p trauma demonstrates posterior displacement and angulation of the femoral head and widening of the physis, consistent with a Delbet Type I fracture

Fig. 2.14 AP radiograph of the right hip in a 15-year-old female figure skater after fall demonstrates a transcervical femoral neck fracture consistent with a Delbet Type II fracture (*black arrowheads*)

degrees of depression of the articular surface. Osteochondral fractures are discrete cortical fractures circumscribing an area of subcortical marrow fat with an intact articular surface [27]. While this precise classification system is not used in common practice, the presence of subcortical injury is important to recognize because it may have important short- and long-term prognostic implications for the patients. The correct identification of the fracture may provide an explanation for the patient's symptoms in the short term, and may also help guide appropriate treatment in order to avoid best outcome in terms of overlying chondral integrity in the long term [27].

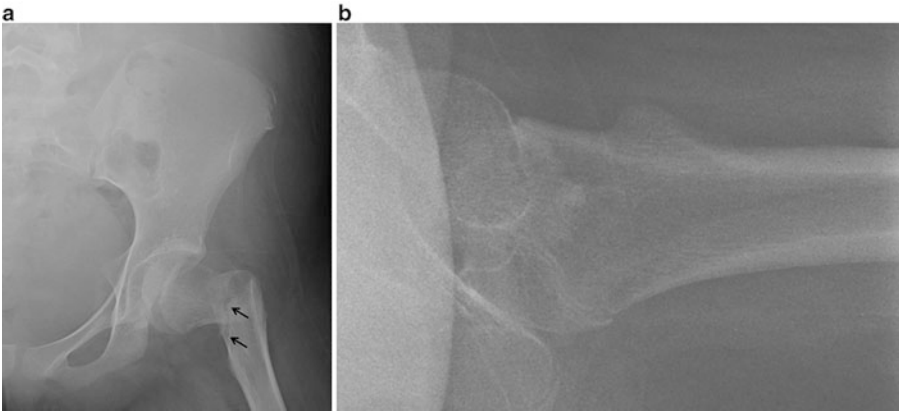


Fig. 2.15 (**a**) AP radiograph of the left hip in a 12-year-old female demonstrates a fracture through the cervicotrochanteric portion of the femoral neck. (**b**) Lateral radiograph of the left hip in a 12-year-old female demonstrates a fracture through the cervicotrochanteric portion of the femoral neck

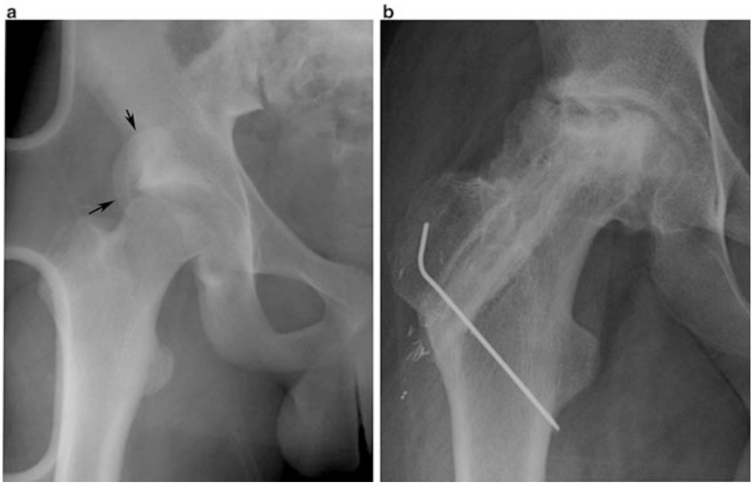


Fig. 2.16 (**a**) AP radiograph of the pelvis in a 14-year-old male s/p MVA demonstrates traumatic epiphyseal separation of the right femoral head (*black arrows*) from the femoral neck, with posterior displacement and lateral rotation of the head with respect to the acetabulum. (**b**) AP radiograph of the pelvis in a 14-year-old male s/p MVA 4 years after injury demonstrates sclerosis, fragmentation, and collapse of the femoral head with joint space narrowing and degenerative changes, consistent with end-stage avascular necrosis. Post-surgical changes related to prior fibular graft are noted within the femoral neck

Radiographically Occult Fractures

Most femur fractures are detected at plain radiography. Equivocal findings should prompt additional views, such as oblique and/or cross-table lateral radiographs. Even with additional views, approximately 2 % of pediatric femoral fractures will have no radiographic abnormality [28]. Most will be subarticular injuries or Salter-Harris fractures [19], which are well appreciated with MRI. MRI should, therefore, be considered in a child with persistent thigh or knee pain after injury to evaluate for occult fracture or other soft tissue abnormality.

Fig. 2.17 AP radiograph of the entire right femur in a 12-month-old male demonstrates an obliquely oriented fracture through the mid to lower shaft of the femur (*black arrow*)

Fig. 2.18 Lateral radiograph of the femur in a 6-year-old male s/p MVA demonstrates a comminuted fracture through the midshaft of the left femur with anterior angulation of the distal fracture fragment and an anteriorly positioned, overlapping fragment (*black arrow*)

Imaging of Fractures in Infants and Neonates

Femur fractures in infants and neonates are uncommon, mainly because these patients are nonambulatory [29]. Fractures in children under the age of 2 years, particularly those children who are not yet walking, are highly suspicious of child abuse [29–31]. Patients younger than 18 months old with femur fractures are more likely to be victims of abuse than accidental trauma [32]. If a non-ambulatory child presents with a femur fracture, a careful history should be elicited to determine if the mechanism put forth could reasonably explain the injury.

Metaphyseal irregularities and periosteal new bone formation are the most common signs of injuries to the long bones of abused infants [33]. The classic metaphyseal lesion (CML) was originally described by Dr. Caffey in 1957 [34] and is a high-specificity indicator of abuse [35]. The distal femur and proximal tibia are the most common sites for the classic metaphyseal lesion in abused infants [36]. This type of injury is a planar fracture through the bone rather than a circumferential fracture, giving rise to various imaging appearances. A “corner fracture” appearance of the CML will be visible with a triangular, peripheral metaphyseal component of the fracture projects tangentially (Fig. 2.29), whereas the fracture will have a more “bucket-handle” configuration if the knee is flexed and the fragment projects at an obliquity [33] (Fig. 2.30). Given the subtlety of these particular fractures, radiographs should be performed with high-detail imaging systems when such a fracture is suspected, with careful attention directed to the metaphyses.

Injuries to the proximal femoral physis in the non-ambulatory child are less common than distal epiphyseal injuries, but also highly correlated with abuse [37] (Fig. 2.31). However, infants may sustain a proximal femoral epiphyseal injury as a result of birth trauma. In these rare instances, if history of difficult delivery is not provided, and the healing response is not appropriate for a birth injury, abuse must be considered. Plain radiographs in the acute stage may not demonstrate the fracture, given that the femoral head is not yet ossified in infants younger than 4 months.

In infants with a proximal femoral epiphyseal separation type of injury, radiographs may be misinterpreted as developmental hip dysplasia (DDH) if the femoral shaft is not aligned with the acetabulum. Ultrasound is helpful in differentiating fracture

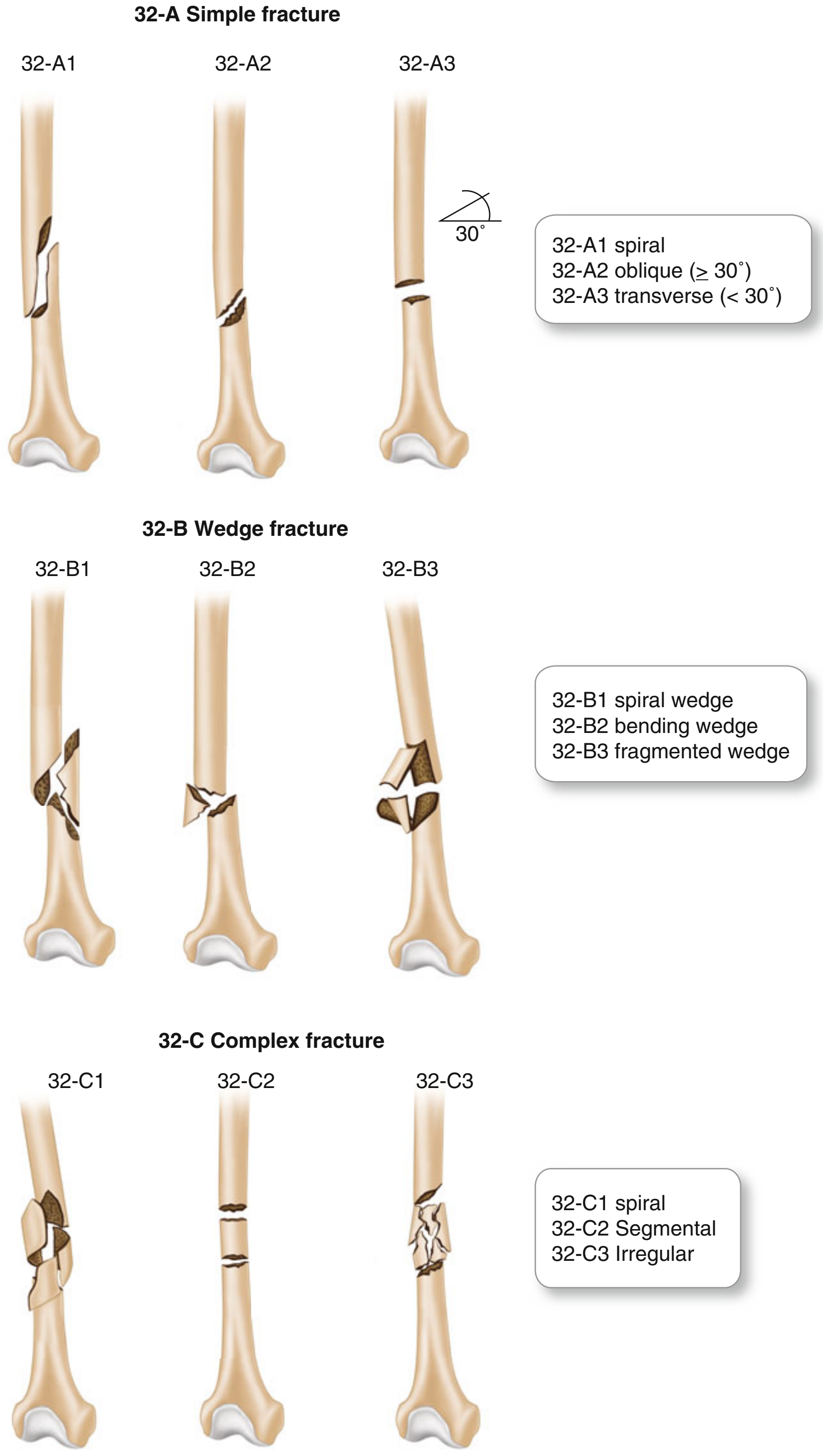


Fig. 2.19 AO classification of femoral shaft fractures

Fig. 2.20 AP radiograph of the right femur in a 16-year-old male s/p MVA demonstrates a comminuted fracture through the distal shaft of the femur as well as several punctate foci of gas within the soft tissues (*white arrows*), indicating an open injury

from dislocation by demonstrating the non-ossified femoral head within the acetabulum. Another benefit of ultrasound is identifying fractures at or near the growth plate in infants and neonates, including epiphyseal separation injuries. With ultrasound, the bone may be imaged in a circumferential fashion, whereas with radiographs two orthogonal views are often all that are available. Subtle growth plate injuries or metaphyseal fractures may be detected with ultrasound (Fig. 2.32). Soft tissue thickening and edema is often seen alongside osseous fractures at ultrasound. As the fracture begins to heal, radiographs become much more helpful in identifying the injury and evaluating healing and alignment. Once the proximal and distal femoral ossification centers have begun to ossify, ultrasound is rarely indicated in the evaluation of femoral fractures.

Imaging Findings Associated with Complications of Pediatric Femur Fractures

Nonunion and the Assessment of Union

Nonunion in pediatric fractures is rare. In a series of 43 pediatric fracture nonunions at a level I trauma center over a 15-year period, only 2 were in the femur [39]. Fracture healing assessment, however, is critical in determining the management of all patients following femoral fractures. Although conceptually simple, the working definitions of union and nonunion in the pediatric population vary between clinicians [40, 41].

Assessment of radiographic union most commonly starts with orthogonal conventional radiographs that allows for qualitative assessment of callus formation, loss of fracture line visibility, cortical bridging, and restoration of trabecular bridging (Fig. 2.33). Radiographic union has classically been defined as three out of four cortices demonstrating bony bridging. When there is uncertainty, then oblique radiographs may assist with visualization of the fracture line, which is especially true if the fracture line is in an oblique plane or fixation hardware obstructs visualization in traditional views. While assessment of cortical bridging has been shown to be the most reliable indicator of union [42], this feature may correlate poorly with mechanical strength [43, 44].

When uncertainty persists regarding fracture union, CT is the imaging modality of choice. MDCT has been shown to be more accurate in detecting the extent of healing around orthopedic implants [45]. Hardware density, thickness, shape, and orientation to the gantry affect the degree of artifact generated, as do the scanner properties and post-processing algorithm applied. Settings can be altered to minimize artifact, including slice thickness and pitch, and post-processing techniques may also be employed to reduce artifact (Fig. 2.34a–c) [46].

Implant Failure

When implants are used to stabilize a fracture, during the early healing process there is a balance between the development of union and the potential development of prosthetic and periprosthetic complications. Although clinical features often arise after a complication has occurred, subtle radiographic signs of an impending complication may precede the clinical presentation and are important

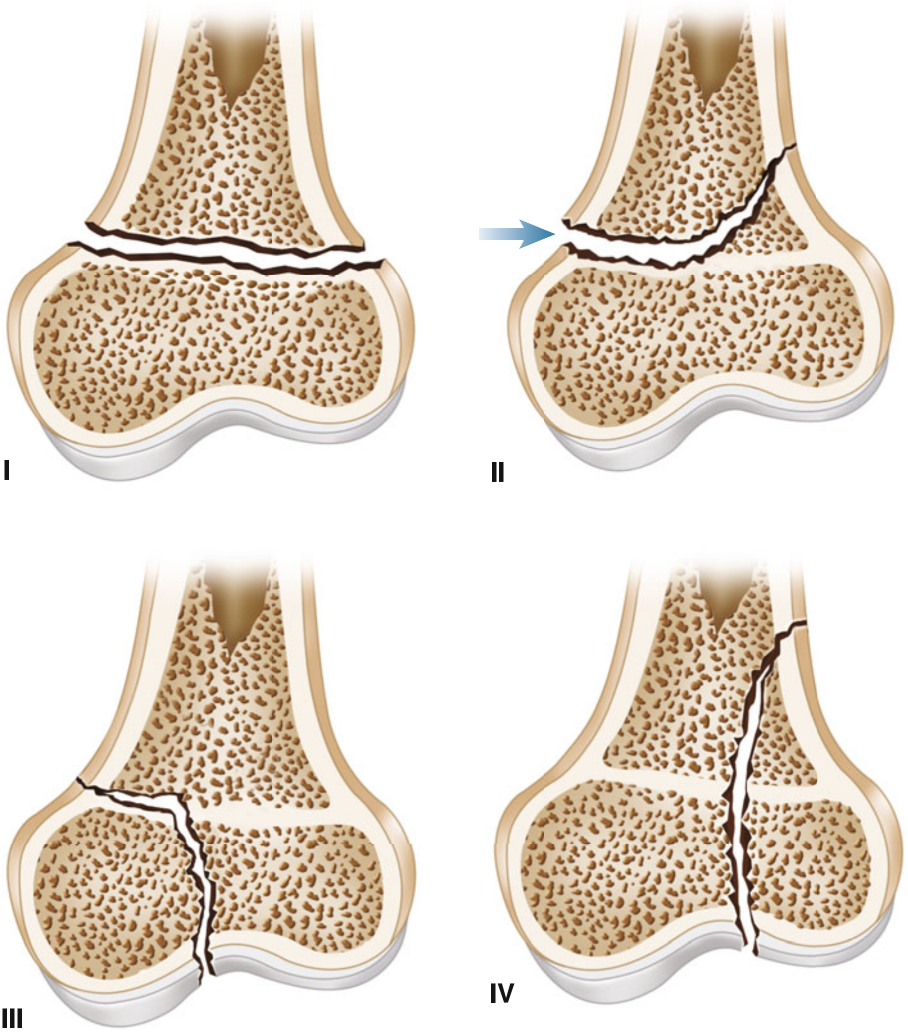


Fig. 2.21 Illustration demonstrating the Salter-Harris classification of physeal fractures

to detect, if possible. Serial radiographs may show changes in fracture alignment or implant position, overt fracture of the implant, or loss of fixation. Where implant motion occurs, radiographic lucencies may develop around screws, which are referred to as halos. Where substantial motion is occurring then an effect called "windshield-wipering" occurs, in which the lucency is wider at the ends where maximal motion is occurring.

Implant fracture occurs when microstructural damage progresses to cyclical loading, then cracking, and finally crack propagation. Radiographic signs that may indicate imminent failure of a plate, rod, or screw includes angular changes within the implant, or ultimately a discrete fracture line within the implant (Fig. 2.35).

Although plain radiographs commonly yield the required information, it has been shown that CT is more sensitive in detecting hardware-related complications [45, 47, 48]. MR is not a preferred modality, as the majorities of orthopedic implants are ferromagnetic and result in substantial artifact without yielding useful clinical information regarding the integrity of the hardware.

Fig. 2.22 (**a**) AP radiograph of the knee in a 15-year-old boy with pain demonstrates an obliquely oriented metaphyseal fracture (*black arrows*) and associated widening of the medial physis (*white arrow*) consistent with a Salter 2 fracture, (**b**) AP radiograph of the knee in a 15-year-old boy 2 weeks later demonstrates an obliquely oriented metaphyseal fracture (*black arrows*) with periosteal new bone formation along the distal shaft of the femur (*white arrowhead*) consistent with healing response

Fig. 2.23 (**a**) AP radiograph of the knee in a 15-year-old female demonstrates a cortical stepoff along the lateral margin of the distal femur at the level of the physis (*black arrow*). No definite fracture lucency is appreciated. (**b**) Coronal reformatted image from a CT scan of the knee in a 15-year-old female demonstrates a metaphyseal fracture within the distal femur (*white arrowheads*) with widening of the physis and abnormal displacement of the lateral femoral condyle with respect to the metaphysis (*black arrow*), consistent with a Salter 2 fracture

Avascular Necrosis

Avascular necrosis (AVN) is a debilitating complication of intra-capsular femoral neck fracture in 8.5–29.3 % of patients, even after surgical intervention has been performed [49]. Avascular necrosis is caused by an alteration in the blood supply to the femoral head. Risk factors for the development of AVN are poorly understood, and include the severity of the initial injury, the time interval between injury and treatment, and type of treatment [50]. AVN is a late complication that may not develop until 18 months to 2 years after the fracture. The radiographic features of the condition demonstrate both the necrotizing and reparative processes that take place in the bone. Radiographs are generally insensitive in the initial stages of osteonecrosis [51]. One of the earliest radiographic features of the disease process is a sclerotic epiphysis and/or a subchondral fissure, fracture, or focal collapse within a section of necrotic bone [51] (Figs. 2.36 and 2.37). This fissure is typically in the anterolateral epiphysis, best imaged with a frog-leg lateral radiograph. Bony resorption follows, with areas of mixed lucency on radiographs, followed by bone deposition and reconstitution of the bony outline [51] (Fig. 2.38).

Early on in the disease process, MRI imaging will demonstrate signal abnormalities within the anterosuperior portion of the femoral head with surrounding bands of dark signal on both T1- and T2-weighted images. MRI is limited, however, in

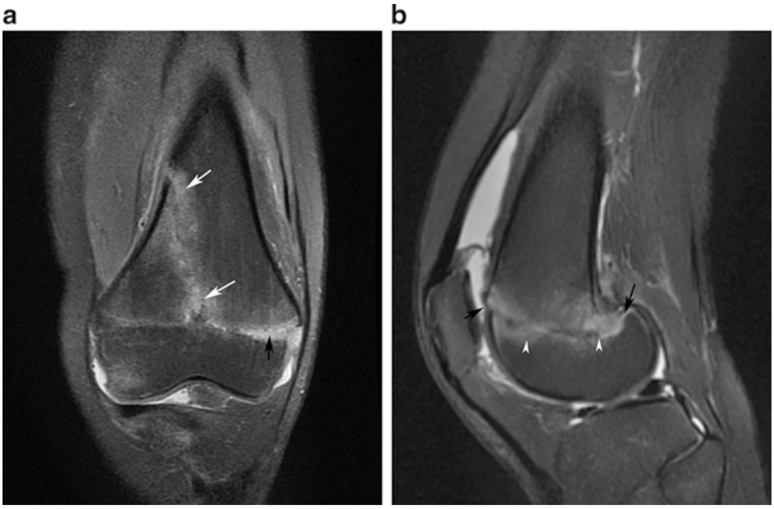


Fig. 2.24 (**a**) Coronal PD-weighted image with fat-suppression through the knee in a 16-year-old female demonstrates a fracture line within the femoral metaphysis with surrounding marrow edema (*white arrows*) and abnormal fluid signal within a widened distal femoral physis (*black arrow*). (**b**) Sagittal T2-weighted image with fat-suppression through the knee in a 16-year-old female demonstrates abnormal edema surrounding the distal femoral physis (*white arrowheads*) with mild posterior displacement of the femoral epiphysis with respect to the metaphysis (*black arrows*). There is also a moderate joint effusion

Fig. 2.25 Sagittal T2-weighted image with fat-suppression through the knee in a 13-year-old female with no injury demonstrates the normal appearance of the bright signal within the distal femoral physis adjacent to the darker signal within the zone of provisional calcification

Fig. 2.26 Coronal reformatted image from a 3D-MEDIC sequence through the knee in a 10-year-old girl demonstrates a central interruption of the otherwise bright distal femoral physis (*white arrowheads*) at the site of physeal bridge

its ability to predict which portions of the femoral head will revascularize and heal. Hyperintense signal in the femoral head on T2-weighted images can be a nonspecific finding in various disease processes, which includes stress injury, infection, and osteopenia.

Currently, approaches to imaging remain relatively suboptimal for prediction of avascular

Fig. 2.27 Sagittal T2-weighted image with fat-suppression through the knee in a 6-year-old male with a Salter 2 fracture demonstrates abnormal fluid signal within the physis (*white arrows*), and entrapment of the posterior periosteum within the physis (*black arrow*). There is also a joint effusion and soft tissue edema

Fig. 2.28 Coronal PD-weighted image with fat-suppression through the knee in a 16-year-old male with a Salter 2 fracture demonstrates a low-signal subarticular fracture line (*white arrowheads*) within the lateral femoral condyle with surrounding marrow edema. Incidental note is made of a NOF within the proximal tibia

Fig. 2.29 Oblique radiograph of the left knee in a 6-month-old male victim of abuse demonstrates an oblique lucency along the posterior margin of the metaphyseal/epiphyseal junction of the left distal femur (*black arrow*), consistent with a "corner fracture," or classic metaphyseal lesion (CML)

Fig. 2.30 Lateral radiograph of the left knee in a 6-month-old male demonstrates a curvilinear lucency along the margin of the metaphyseal/epiphyseal junction of the left distal femur (*white arrows*) consistent with a "bucket-handle fracture," or classic metaphyseal lesion (CML)

necrosis before irreversible damage has occurred. Noncontrast enhanced MRI of the femoral head after acute femoral neck fracture is inadequate to determine the viability of the head and therefore a poor predictor of subsequent AVN [52]. In one study, bone scintigraphy with SPECT (single-photon emission computed tomography) was more sensitive than noncontrast MRI in detecting early osteonecrosis of the femoral heads after renal transplantation [53]. Decreased perfusion to the femoral head after femoral neck fracture manifests in bone scintigraphy as a cold defect in the femoral head (Fig. 2.39a, b). However, while nuclear medicine studies have been the gold standard in the assessment of the vascularity of the proximal femur where potential compromise to the blood supply has occurred, reduced uptake in the acute stage does not always correlate well with eventual development of AVN. A bone scan performed between 2 and 3 weeks post-injury may be used to assess epiphyseal vascularity [6]. MRI with contrast is helpful in assessing the enhancement pattern of the femoral head (Fig. 2.40a–c). Dynamic contrast-enhanced MRI is a technique that allows early detection of ischemic change in the hip [54]. This technique has replaced bone scintigraphy in many centers because of its ability to accurately depict femoral head deformity, cartilage and labral damage, and abnormalities of adjacent soft tissue structures in addition to the perfusion pattern of the femoral head. Reperfusion patterns of the hip are similar between dynamic gadolinium-enhanced subtraction MR imaging and bone scintigraphy in patients with Legg-Calve-Perthes disease (LCP), but have not been investigated extensively in patients with femoral fracture [55]. There is ongoing research investigating the utility

Fig. 2.31 AP radiograph of the left femur in a 7-year-old female victim of child abuse demonstrates abundant callous formation along the proximal femur (*black arrows*) and mild inferior displacement of the femoral head ossification center (*white arrowhead*) consistent with a healing fracture to the proximal femoral physis. A CML at the distal femur is also noted

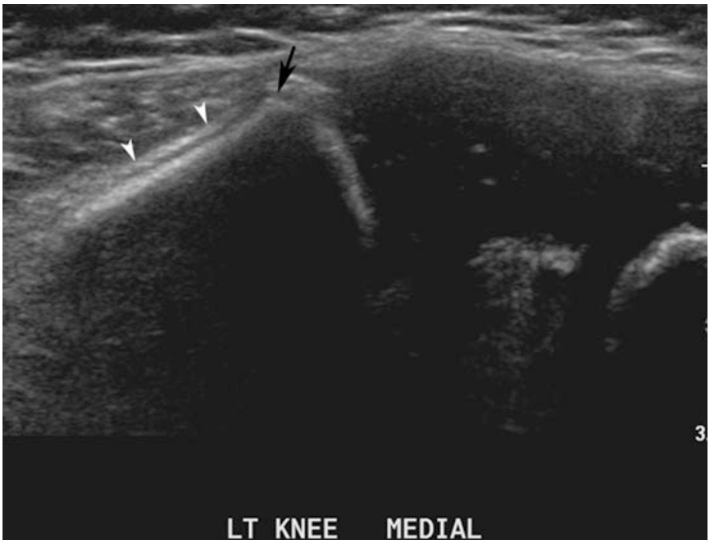


Fig. 2.32 Ultrasound image of the left knee in a 6-month-old female from a medial approach demonstrates early periosteal new bone formation along the distal shaft of the femur (*white arrowheads*). There is a small echolucent fracture line at the metaphyseal/epiphyseal junction (*black arrow*). Of note, the non-ossified femoral condyles appear dark given the lack of ossification

Fig. 2.33 AP radiograph of the right femur in a 12-year-old female 1 year s/p fall demonstrates a hypertrophic nonunion (*black arrows*) despite placement of a rigid intramedullary nail across the fracture site. There is no cortical bridging across the callus, and the fracture line is still visible and irregular in contour

of diffusion-weighted imaging (DWI) in the hip to determine whether changes on diffusion-weighted images correlate with prognosis. DWI detects ischemic changes in tissues by measuring changes in water mobility. Diffusion-weighted imaging has been shown to detect early ischemia in the femoral head in a piglet model [56]. Preliminary studies on human patients with LCP demonstrated the presence of age-related diffusion changes in the femoral head, as well as the development of metaphyseal changes that suggest that DWI may have a future potential role in predicting prognosis [57, 58]. Although these methods have not been proven in pediatric patients with femoral neck fractures, dynamic MR perfusion imaging and diffusion-weighted imaging are likely to be promising techniques for predicting post-traumatic femoral head AVN with further investigation into their efficacy.

Growth Disturbance/Leg Length Discrepancy

Leg length discrepancy is a potential complication of femoral fractures, particularly if the fracture involves the distal femoral growth plate. The distal femoral physis contributes to approximately 50 % of the overall length of the leg [22]. Growth disturbances occur when there has been significant damage to the epiphyseal plate or its blood supply, which may occur with any type of Salter-Harris fracture. Fractures in the proximal femur may lead to varus or valgus deformities depending on the location of the fracture and the pattern of healing (Fig. 2.41). Development of a leg length discrepancy is correlated with the degree of displacement and the quality of the reduction (whether open or closed) [21, 22]. The Salter-Harris classification of physeal fractures also provides an accurate predictor of outcome, with type V fractures requiring more reconstructive surgery to improve function than type I [22]. Growth arrest is usually appreciable within 12–18 months following post-injury [21]. Patients should therefore be followed closely for at least 1–2 years after an injury when the possibility of physeal disturbance exists [59].

An accurate method of measuring the amount of leg length discrepancy is a “scanogram” or “orthoroentgenogram” [60]. On a single film, three exposures are made with the beam centered successively over the hips, knees, and ankles. Two sliding metal shields allow an exposure to be made over one-third of the film while the remainder of the film is protected from exposure. A ruler may be placed at the side of the patient to facilitate accurate measurement of the leg length. Given that the focal spots are directly over each joint, there is no divergence of the beam and therefore no significant magnification of the resultant image. The total lengths of the femurs and tibia may be measured on each side to determine the difference between sides and is a reliable tool for pre-operative planning prior to epiphysiodesis, in which large threaded screws may be placed across the physis or drilling and curettage of the growth plate performed in order to halt the growth on one side of a long bone (Fig. 2.42a, b). Alternatively, a computerized tomography scanogram (CT-scanogram) may be performed utilizing a single AP scout image from the pelvis to the ankles, and acquiring a direct measurement from this image [61].

Fig. 2.34 (**a**) AP radiograph of the right hip in a 15-year-old male s/p fall demonstrates a transcervical femoral neck fracture with medial angulation (*black arrow*) at the fracture site. (**b**, **c**) Reformatted coronal image from a CT scan of the hip in the same 15-year-old male 6 months s/p placement of three screws across the fracture site. The study was performed on a 64-detector CT scanner using metal reduction post-processing algorithm, allowing the fracture line to remain clearly seen (*black arrows*) secondary to the relatively minimal streak artifact related to the metal hardware

Fig. 2.35 AP radiograph of the right femur in a 16-year-old male with an intramedullary rod and distal interlocking screw spanning a healing midshaft femur fracture demonstrates a crack in the interlocking screw (*black arrow*) and an angulation in the screw at the level of the discontinuity

Fig. 2.36 AP radiograph of the right hip in a 12-year-old male s/p MVA who suffered a dislocation/relocation injury to the right hip treated with surgical dislocation, screw fixation of Pipkin fracture, and posterior labral refixation/repair demonstrates a sclerotic femoral head (*black arrow*) consistent with development of AVN 4 months after injury

Fig. 2.37 Frog-leg lateral radiograph of the left hip in a 12-year-old female 9 months s/p surgical repair of a femoral neck fracture with three femoral neck screws demonstrates early, subtle sclerosis within the head with mild flattening of the anterior femoral head contour associated with a subtle subchondral fissure (*black arrow*), representing early radiographic changes of AVN

Fig. 2.38 AP radiograph of the right hip in a 12-year-old male s/p MVA who suffered a dislocation/relocation injury to the right hip treated with surgical dislocation, screw fixation of Pipkin fracture, and posterior labral refixation/repair demonstrates a sclerotic femoral head (*black arrow*) consistent with progression to end-stage arthrosis secondary to AVN 16 months after injury

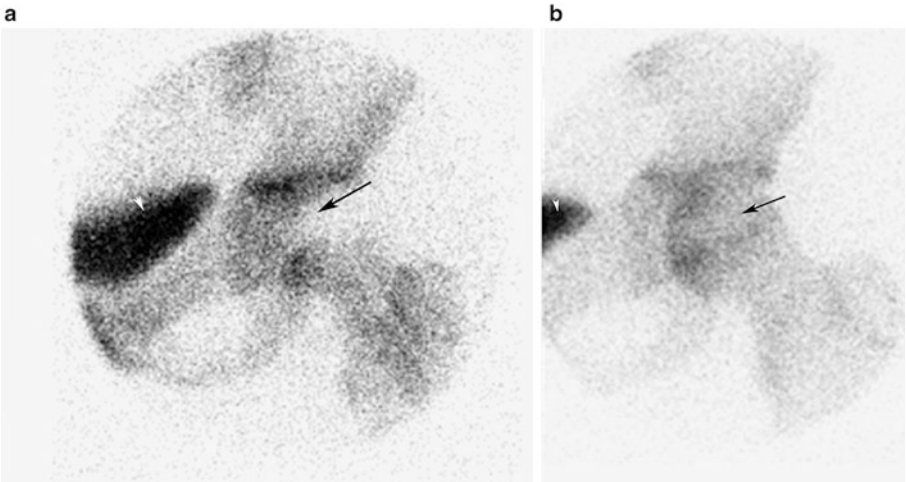


Fig. 2.39 (**a**) AP pinhole collimated image of the left hip from a bone scintigraphy study on a 6-year-old patient 4 days s/p open reduction and internal fixation of the left hip for femoral neck fracture demonstrates no perfusion to the femoral head (*black arrow*). The *white arrowhead* denotes the bladder. (**b**) AP pinhole collimated image of the left hip from a bone scintigraphy study on a 6-year-old patient 4 months s/p open reduction and internal fixation of the left hip for femoral neck fracture demonstrates improved perfusion to the femoral head (*black arrow*). The *white arrowhead* denotes the bladder

Physeal Bridge

Though “scanograms” are well suited for evaluating the severity of a patient’s growth disturbance, they are not suited for evaluating bony physeal bridges that directly contribute to the growth disturbance. The size and location of bony bridges are important factors for determining prognosis and indications for surgery. MRI is the preferred modality for evaluating such

Fig. 2.40 (**a**) AP pelvis radiograph in a 16-year-old male s/p motorcycle accident demonstrates a comminuted left transcervical femoral neck fracture with mild angulation and a free fragment inferior to the neck (*black arrow*). (**b**, **c**) Coronal T1-weighted image without contrast through the hips in the same patient one year after injury demonstrates flattening and sclerosis within the superior aspect of the femoral head (*black arrow*) representing an area of avascular necrosis. Post-surgical changes are noted within the femoral neck related to prior hardware placement and removal

Fig. 2.41 AP pelvis radiograph in a 5-year-old female s/p bilateral proximal femoral physeal fractures in infancy, now with post-traumatic coxa vara deformities (*black arrows*)

physeal abnormalities. Fat-suppressed three-dimensional (3D) spoiled gradient-recalled echo (SPGR) sequences are very useful for identifying patterns of growth arrest in children after physeal insult due to high spatial resolution, multiplanar imaging capabilities, and excellent contrast between bone and cartilage signal [62–64]. Bony bridges are well visualized on 3D-SPGR sequences as a low-intensity zone within the physis, iso-intense to suppressed fatty marrow, and hypo-intense to the adjacent cartilaginous physis [62]. Maximum intensity projections (MIPs) of the juxtaphyseal area in the axial (transverse) plane allow mapping of the area of bony bridging and determination of the size of the bridge relative to the entire phy-

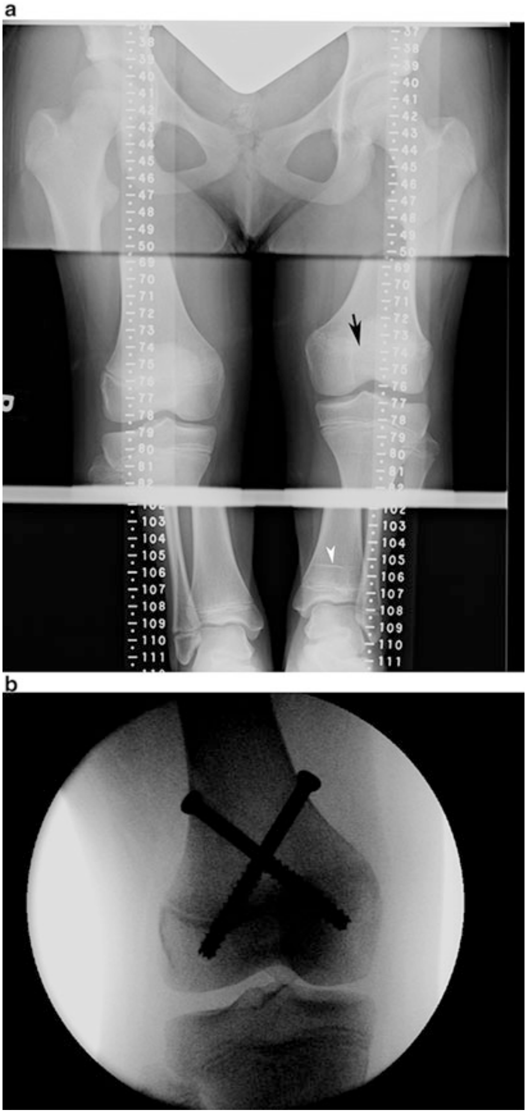


Fig. 2.42 (**a**) Scanogram (orthoroentgenogram) on a 12-year-old female 18 months after sustaining a physeal fracture to the left distal femur. The left distal femoral physis has fused (*black arrow*) earlier than the right side, and there is a nearly 2 cm leg length discrepancy. Incidental note is made of a growth recovery line in the distal left tibia (*white arrowhead*). (**b**) Fluoroscopic spot images from a screw epiphysiodesis in a 12-year-old female 18 months after sustaining a physeal fracture to the left distal femur. Two cannulated screws were placed across the distal femoral physis of the right knee to correct for the growth disturbance on the left

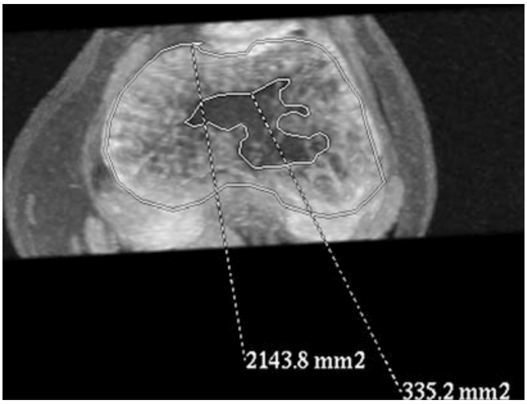


Fig. 2.43 Axial maximum intensity projection (MIP) image from a 3D-SPGR sequence in the knee of an 11-year-old girl who sustained a Salter 2 fracture of the distal femur 7 months ago. The area of the physis and a central physeal bone bridge were measured on a workstation, which reveal that the bone bridge spans ~15 % of the physis

sis (Fig. 2.43). On T1-weighted images the bone bridge demonstrates high signal intensity, unless the bridge is small in which case the signal may be variable in intensity. The distal femoral physis is particularly vulnerable to premature physeal bridging after trauma, likely related to a complex undulating pattern in the central physis corresponding to an area of early physiologic closure [65]. Growth recovery lines are also indicators of growth disturbance. Often identified as thin, linear sclerotic bands on radiographs in proximity to the physis, these bands are best visualized at MRI on T1-weighted images as low-intensity bands surrounded by high-intensity fatty marrow [62]. The orientation of the growth recovery line often serves as indicator as the location and size of the physeal bridge. Peripheral bone bridges tend to be small and lead to tethered growth recovery lines that are angled relative to the physis [62]. Central bony bridges produce growth recovery lines parallel to the physis, and are of variable size.

Infection

Infection is an uncommon complication of femur fractures. Imaging rarely plays a significant role in patients with early wound infections after surgery, as it takes at least 2 weeks for radiographic features of infection to manifest. Abnormal and

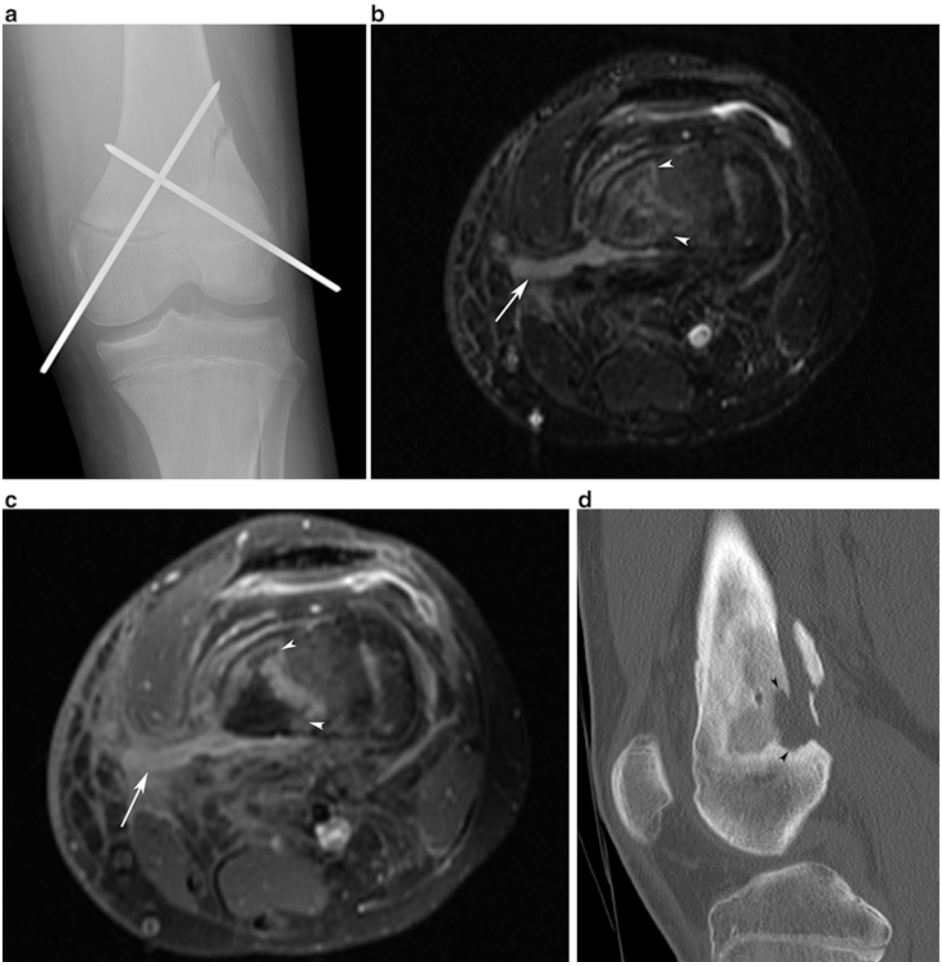


Fig. 2.44 (**a**) AP radiograph of the knee in a 15-year-old male s/p Salter 2 fracture demonstrates two K wires spanning the fracture through the distal femur and physis. (**b**) Axial T2-weighted fat-suppressed image through the knee in the same 15-year-old patient 3 weeks after surgery. The pins were removed because they became exposed. MRI reveals an area of signal abnormality within the distal femur (*white arrowheads*) and a bright tract extending from the bone to the subcutaneous soft tissues (*white arrow*), representing an area of infection. (**c**) Axial T1-weighted, post-contrast, fat-suppressed image through the knee in the same 15-year-old patient 3 weeks after surgery reveals a rim-enhancing area of signal abnormality within the distal femur (*white arrowheads*) consistent with an intra-osseous abscess, and an enhancing tract extending from the bone to the subcutaneous soft tissues (*white arrow*), representing a draining sinus. (**d**) Corresponding sagittal reformatted image from a CT scan through the knee in the same 15-year-old patient 3 weeks after surgery reveals an area of low attenuation within the distal femur and focal bony destruction (*black arrowheads*) corresponding to the abscess detected at MRI

increasing lucency around metallic hardware is one early radiographic sign of infection, but may also be seen in the setting of hardware loosening.

Sonography may be useful to evaluate for soft tissue infection adjacent to orthopedic devices, including soft tissue abscess and bursitis, but is not as useful for imaging the bone. CT and MRI imaging better demonstrate bone detail (Fig. 2.44a–d). Imaging a post-operative orthopedic patient with cross-sectional imaging may be challenging given the artifacts associated with most implants at CT and MRI. These artifacts, however, are becoming increasingly easier to manage with advances in imaging technology. Titanium implants result in the least amount of CT and MR artifact [66]. Artifact may be further reduced at CT by careful positioning of the patient in the scanner, and meticulous post-processing algorithms. Faster MRI imaging techniques have resulted in decreased metal artifacts relative, and wider readout bandwidths may be employed to reduce metal artifact [66].

CT imaging findings of infection in a patient with hardware include periosteal reaction, areas of focal lucency, sequestra, areas of bone sclerosis, and soft tissue fluid collections [47]. These findings, however, are not specific for infection. At MRI areas of abnormal bright signal on fluid-sensitive sequences surrounding hardware and fracture sites may indicate possible infection, but these findings are nonspecific. 18F-FDG PET/CT imaging combines the anatomic localization of CT with functional PET imaging, and is the first line cross-sectional imaging study in patients with suspected spinal hardware infection [67]. This technique may also be useful in a patient with a suspected hardware infection after femur fracture, and provides greater specificity for infection that CT alone.

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Femur Fractures in Neonates, Infants and Toddlers with or Without Child Abuse

3

J. Lee Pace and David L. Skaggs

Introduction

Femur fractures in the neonate, infant, and toddler have a subset of unique challenges. The very young child has a dramatic and rapid healing response. Long-term outcomes for femur fractures in this age group are good, and treatment is typically non-surgical. Child abuse and metabolic/developmental conditions must be considered in these patients as well.

Birth Trauma/Neonatal Fractures

Obstetric Fractures

The obstetric femur fracture is specific to the event of delivery, in both vaginal and abdominal births (via C-section). While risk factors exist that can predispose a fetus to a fracture during delivery, it can occur in a normal child during an otherwise normal delivery. Neonatal femur fractures, or fractures that occur shortly after birth, tend to occur in children with additional risk factors, such as prematurity, child abuse, metabolic conditions related to prematurity, and underlying conditions such as osteogenesis imperfecta (OI).

Despite the excellent healing and remodeling potential for these injuries, they can create stress and concern for the family following the birth of their child. While no prospective studies currently exist, one retrospective review from Ireland determined an incidence of 0.13 per 1000 live births at their hospital [1]. Historically speaking, obstetrical femur fractures were typically considered iatrogenic from excessive traction and/or torque during a difficult breech delivery or attempts at version [2–10]. With Caesarean section becoming more routine for fetuses in the breech position [8, 11], most recent studies have reported fractures occurring during Caesarian delivery for breech, and occasionally for non-breech, presentation [2, 3, 7, 12–28]. While rare, femoral fractures have been reported during vaginal delivery for cephalic presentation as well [1, 3].

Mechanism

The common mechanism for most obstetric-related fractures appears to be excessive traction and/or torque during a difficult delivery. For a vaginal breech delivery, traction on the thigh after the breech is fixed at the pelvic inlet or

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improper handling during shoulder and arm delivery can cause the fracture. While Caesarian delivery for breech presentation is thought to lessen the risk of femur fractures during delivery, there is some thought that since abdominal and vaginal delivery methods are similar, the risk of femur fracture from Caesarian delivery persists [22, 27]. External cephalic version of the infant in utero has also been implicated [9].

In modern times, Caesarian section has become the common method of delivery for fetuses in the breech position [8, 11]. As such, most current reports of obstetric femur fractures involve Caesarian delivery. There are likely several ways during a difficult breech extraction that a femur fracture can occur. Commonly cited risk factors, as shown in Table 3.1, include small uterine incisions [4, 16, 20, 22, 26], large or very small birth-weight babies [3, 12, 14, 22, 23, 29], an impacted extremity in the pelvis during extraction [17, 20], uterine fibroids [4, 17], twin pregnancies [1], inadequate uterine relaxation [20], and associated metabolic- and neuromuscular-related conditions, etc. [29–34]. In some reports, no risk factor is identified [17, 20, 21, 25, 27, 28].

Location

Most obstetric-related fractures occur in the femoral shaft [1], however, fractures along the entire length of the femur have been reported. Notable reports in the literature include physeal separations of the proximal [6, 12, 35–40] and distal [6, 21, 29, 33, 36, 41] femoral epiphyses, distal metaphyseal fractures [7, 9, 25], and subtrochanteric fractures [27]. The proximal femoral epiphyseal fracture in the neonate is unique in that the femoral head and neck as well as the greater and lesser trochanters are avulsed off as one piece from the proximal shaft [40].

Table 3.1 Risk factors for obstetric femur fracture

Risk factors	Diseases/conditions
Large or small birth weight babies	Osteogenesis imperfecta
Small uterine incisions during C-section	Cerebral palsy
Uterine fibroids	Multisynostotic osteodysgenesis
Impacted extremity in pelvis during abdominal extraction	Spinal muscular atrophy
Inadequate uterine relaxation	Spina bifida/myelomeningocele
Twin pregnancies	

Fig. 3.1 Atraumatic subacute left femur fracture (*arrow*) in a neonate with multisynostic osteodysgenesis that was picked up incidentally on a chest and abdomen X-ray. Also noted are the characteristic bilateral humeroradial synostoses with an associated humerus fracture, right femoral bowing, bilateral teratologic hip dislocations, and evidence of obstructive micrognanthia s/p jaw distraction. The patient was in the NICU at the time of the fractures. Used with permission of the Children's Orthopaedic Center, Los Angeles, CA

Neonatal Fractures

Femur fractures in the neonatal period (first few weeks of life) often occur in settings and/or conditions such as OI, prematurity, and child abuse [15, 30, 32, 42–45] (Fig. 3.1). With the exception of the abused child, these children are often hospitalized when the fracture occurs, which can result from minor extremity manipulation [1, 15, 32, 33, 42, 45–47]. Very low birth weight (VLBW) infants (<1500 g) have been reported to have a total fracture incidence of 2–10 % [46, 48].

This may be an underestimate, as some fractures (ex: rib fractures) likely go undiagnosed [46, 48]. When femoral fractures occur in VLBW infants, they tend to be in the metaphysis or diaphysis [15, 30, 32, 42, 45–48]. Determining the cause of the fracture may require a more thorough workup, for the reasons listed above. Often these patients will require a head-to-toe physical examination to look for associated abnormalities, including lab work, imaging, and a multidisciplinary team approach to find an underlying cause. If an otherwise healthy, term neonate has a femur fracture, child abuse should be suspected [34, 49–53].

Physiologic Factors

In preterm neonates, rickets has been recognized and described as a risk factor for fracture in VLBW infants [46, 48, 54]. The incidence of rickets in this population is not well known but reports suggest that at least 10–20 % of preterm neonates that weigh <1000 g have radiographic signs of rickets [54, 55]. Further, preterm neonates with alkaline phosphatase (ALA) levels >1000 IU/L may have a 50–60 % incidence of rickets [54]. Conditions in the preterm neonate that may cause or exacerbate rickets include cholestasis (which impairs metabolic production of Vitamin D), bronchopulmonary dysplasia (in which the infant is given steroids and/or loop diuretics which tend to increase urinary excretion of calcium), and prolonged parenteral feeds that have not been properly supplemented with calcium, phosphorus, and Vitamin D [43, 46, 54]. While an in-depth discussion of the physiology of rickets is beyond the scope of this chapter, the recognition of it in this patient population is paramount so that appropriate supplementation with calcium, phosphate, and Vitamin D can occur to reverse the rickets and prevent further fractures [43, 54]. Often, pre-pumped breast milk and/or formula can be fortified with these vitamins and minerals specifically for preterm neonates, and parenteral feeds can be altered to increase the availability of these nutrients [54].

Presentation and Diagnostic Modalities

Most patients in this age group with femur fracture present with "pseudoparalysis," or unwillingness to move the affected extremity. Swelling and tenderness to palpation are typically present as well. Notably, this is also how an orthopedic infection such as osteomyelitis or septic arthritis presents in this age group and should therefore be on the differential diagnosis [56–58]. While the vast majority of femur fractures are easily diagnosed via plain radiographs, physeal fractures in this early age group may be missed using this modality [6, 12, 21, 29, 41, 59]. In these situations, the clinician should consider other diagnostic tools such as magnetic resonance imaging (MRI) and ultrasound (US) [29, 37, 59], which are useful for physeal injuries as well as for detecting infection. Computed tomography (CT) can also be utilized [29], but should be a third option due to radiation exposure and the degree to which femoral structure remain non-ossified in this age group. Arthrography can also be considered as an adjunct if other modalities are unavailable [29]. Laboratory tests such as C-reactive protein, erythrocyte sedimentation rate and white blood cell counts should be ordered if an infection is suspected.

Infantile and Toddler Fractures

As children exit the neonatal phase of life, they become more mobile and start crawling and eventually walking. This mobility increases their risk of sustaining an accidental femur fracture, usually from a fall [60–62]. Child abuse is still a significant cause of injury in this age group, and the clinician must keep this possibility in mind [60–64]. This is particularly true if the child is not yet walking. In the pre-ambulatory period of life, the child generally cannot generate enough energy on his or her own to sustain a femur fracture. Thus, most femur fractures in the pre-ambulatory age group are secondary to non-accidental trauma (NAT), high-energy trauma such as falls (typically a fall by a caregiver or a crawling child who falls down stairs, as opposed to a fall in an ambulatory child), motor vehicle accidents, and conditions of bone fragility, such as OI [33, 34, 43, 47, 60–63, 65–69]. Femoral fractures as they relate to child abuse will be discussed in a later section. Once the child begins walking, twisting mechanisms from accidental trauma become more common, although child abuse is still frequently seen [62, 70–72].

Epidemiology

There is some variation in how the incidence of pediatric femur fractures is reported. The Hospital Discharge Database of the Maryland Health Services Commission was reviewed between 1990 and 1996 and determined an annual fracture rate of 25.5/100,000 in children <2 years of age in the state of Maryland [73]. A study analyzing the 2000 Healthcare Cost and Utilization Project Kids' Inpatient Database (KID) reported that of 10.8 % of all femur fractures occurred in children <2 years of age [62]. This database records data on pediatric hospital discharges for most U.S. states. A month-by-month analysis of the 1997 KID database showed a bimodal distribution of femur fracture incidence with a peak occurring around 3 months of life and again around 20–40 months [61]. The rate of fracture for children less than a year of age was 43/100,00; for children at 1 year of age the rate was 33/100,000; and a rate of 42/100,000 was observed for children 2 years old. A review of the Colorado Trauma Registry between 1998 and 2001 determined a rate of 29.4/100,000 person-years in the 0–3 age group in that state [71]. A Swedish study examined femoral fractures from their Inpatient Care Register and determined an incidence of just less than 2 per 10,000 person-years for children <2 years old [63].

In all studies examined, males sustained the majority of fractures. In older age groups, males sustained as much as 70 % or more of all femur fractures. In the infant and toddler age group, however, the fracture rate between genders was much closer. The 2000 KID database study determined that females accounted for 40 % of fractures in the 0–2 age group [62]. The previously mentioned Swedish study found an equal rate of fracture among genders in the 0–1 and 2–3 year age groups [63]. The Maryland and Colorado studies also found near equal annual fracture rates between genders in the first year of life, as did the 1997 KID database study [61, 66, 71, 73]. The 1997 KID database study, which looked at fracture rate by month, also found a peak in fracture rate around 3 months of age in both genders during the first year of life. With children of ages greater than 2 years, females had an overall lower rate of fracture consistent with older age group demographics. All authors suggested this closer gender gap was likely due to the high incidence of child abuse seen in infants and young children [61–63, 71, 73].

Race and socioeconomic status also affect fracture rates. This tends to hold true for all age groups. The Colorado and Maryland studies examined this and found that racial minority patients, patients with low socioeconomic status, and patients with single mothers as head-of-household were at more risk of sustaining a femur fracture [71, 73].

Mechanism and Location

Femur fractures in infants and toddlers are most frequently due to falls and child abuse [43, 50, 60, 62, 68, 71, 73–78]. In patients less than 3 years, approximately 50–65 % of all accidental femur fractures are attributed to falls [62, 71, 73]. Less frequent are motor vehicle accidents and pedestrian vs. auto accidents [60, 62]. About 65–70 % of femur fractures in children <2 years occur in the femoral shaft [62, 71, 76]. In accidental trauma, especially in children who do not yet ambulate, it is common for the patient's caretaker or older sibling to fall while carrying the child or fall onto to the child [67, 69]. In these situations, fractures are typically buckle/impaction fractures of the distal metaphysis or spiral/long oblique or transverse/short oblique fractures of the mid-shaft [69]. Fewer accidental femur fractures (and for that matter, fractures due to child abuse) occur in the proximal femur or distal epiphysis. When they do, they are typically, but not always [53], related to a high-energy mechanism such as being involved in a car accident or being struck by a car or other fast-moving object [62, 69, 71, 76].

Treatment

Treatment is often dictated by age and/or weight of the child, despite lack of any reports describing a weight-based algorithm [79].

Obstetric and Neonatal Fractures

Traction and long leg or spica casting for shaft and metaphyseal femur fractures in neonatal and obstetric fractures have been described [1, 9, 20, 28, 45, 47, 80]. However, more recent reports describe use of a Pavlik harness for these fractures [64, 79, 81–83], and the authors prefer the Pavlik harness technique for these fractures in patients who are large enough to fit in one, which typically excludes premature infants. The technical details for using the Pavlik harness are described below. Traction (e.g. Gallow's [45] or Bryant's [40]) has largely fallen out favor in the United States due to compartment syndrome risk [84] and need for prolonged immobilization [45]. While this is an option, the authors prefer splinting of these injuries. Splinting is typically makeshift and can include a plaster slab and bias wrap, but can also be successfully accomplished with something as simple as a tongue depressor and a gauze wrap. The latter may be more appropriate for the VLBW infants because the weight of a plaster splint may be excessive. It is vitally important that the limbs are not wrapped too tight, and that frequent neurovascular checks are performed. Gentle elevation may help control swelling. The authors do not typically perform spica casting for femur fractures in this patient group.

Epiphyseal injuries in this group have been treated with closed and open methods [4, 6, 12, 21, 29, 36, 37, 41, 59]. It is difficult to draw firm conclusions about treatment for these injuries because most literature is in the form of case reports and many reports are at least 30 years old [6, 7, 12, 39, 41, 85]. This entity is either being seen less or is being reported less often today. Some authors speculate this may be due to improved obstetric practices [38].

Distal femoral physeal fractures are typically treated with closed reduction and immobilization, or even immobilized in situ and allowed to remodel. Sometimes, there is a delay in diagnosis such that callous formation has already occurred and the physician has no choice but to allow the fracture to remodel. Riseborough et al. included five patients with obstetric distal femoral physeal fractures in a larger study of these injuries in a mixed age group of pediatric patients [10]. All fractures were treated closed without an attempt at reduction. While functional outcomes are not detailed in the manuscript the authors note that only one patient out of the five with obstetric fractures had a significant leg length difference of 2.8 cm, which the authors believed was due to anisomelia [10]. Other case reports and small series demonstrate good outcomes with no clinically significant growth disturbances, angular deformities or functional impairments [21, 44, 59]. There are reports of fractures managed conservatively with no reduction attempt that resulted in clinically significant leg length discrepancies at long-term follow-up [36]. Case reports of closed reduction and pinning of these injuries with a smooth Kirschner wire have demonstrated good results with no growth disturbances noted [29, 44]. Making treatment recommendations from this is difficult. Minimally displaced distal femoral physeal fractures likely do well with conservative management with in situ immobilization, while highly displaced fractures (i.e., where the epiphysis is displaced 100 % or more), should have an attempt at reduction and potential surgical stabilization. If the fracture is older than 5–7 days or the age of the fracture is uncertain, it may be best to treat with in situ immobilization to minimize further damage to the growth with attempts at reduction, though there is no literature to support this recommendation.

Proximal epiphyseal fractures, sometimes called proximal femoral epiphysiolysis, owing to the unique fracture pattern described above, are similarly rare. Ogden et al. reported on seven neonatal proximal femoral physeal injuries, five of which were from obstetric injury and two from child abuse [40]. Six were treated in traction followed by either an abduction brace or cast, while one was casted from the outset. All but two of the fractures fully remodeled with no functional deficits. One patient had mild residual deformity with no functional deficits and the remaining patient, who was a child abuse victim, had complete proximal physeal arrest by 5 years of age and had undergone multiple corrective procedures [40]. The remainder of the literature tends to report similar findings in which most of these injuries remodel fully with little to no sequelae [6, 12, 37–39, 85, 86]. The remainder most often develop a coxa vara deformity, as well as possible rotational deformities or leg length discrepancies that may require corrective procedures [35, 36, 40]. There are reports of operative fixation of these injuries but the numbers are too few to determine if these results are any different than conservative treatment [35, 87]. As with distal femoral physeal injuries, if the fracture is 5–7 days old or of uncertain age, in situ immobilization is the preferred treatment, as manipulation may cause iatrogenic injury to the growth plate.

Infant and Toddler Fractures

The two mainstay treatments for diaphyseal femur fractures in this age group are the Pavlik harness and the spica cast; with the harness typically being reserved for patients less than 6 months to a year and spica casting for patients greater than 6 months of age. Recently, the American Academy of Orthopaedic Surgeons (AAOS) published a clinical practice guideline for the treatment of pediatric diaphyseal femur fractures. The clinical workgroup considered a Pavlik harness an option for treatment along with a spica cast for patients less than 6 months of age [64, 79]. They further recommended early spica casting vs. traction followed by delayed spica casting for patients aged 6 months to 5 years [79]. These were Grade C and B recommendations, respectively based on relative paucity of literature. Most subtrochanteric femur fractures can be managed with these modalities in the infant and toddler age group as well but further discussion of these fractures as well as other metaphyseal and epiphyseal fractures will be reserved for other chapters. The technical details of spica cast application and care are dealt with in a subsequent chapter as well, so the remaining discussion in this section will focus on the Pavlik harness.

Pavlik Harness

Stannard et al. first reported use of the Pavlik harness for obstetric and neonatal femur fractures in 1995. They produced a prospective cohort study of 16 fractures in 14 patients with a minimum 12-month follow-up (range 12–30, mean 20) in 11 patients. Age of the patients ranged from birth to 18 months. One patient with OI had three femoral fractures. All were treated with a Pavlik harness. All fractures were proximal or mid-shaft and all united in acceptable alignment with less than 1 cm of shortening [82]. Union was achieved by 4–5 weeks in all fractures, and the harness was discontinued at that time. No complications such as femoral nerve palsy, skin breakdown, etc. were reported. At final follow-up, no malunions or leg length discrepancies >1 cm were noted. The authors felt this treatment was appropriate for patients <4–6 months of age if size appropriate, fractures of the proximal or middle shaft, and shortening of <2 cm.

Podeszwa et al. later reported on treating children up to 1 year of age in a Pavlik harness. They retrospectively compared 24 patients under 1 year of age with a femoral shaft fracture treated with a Pavlik harness to 16 similarly aged patients treated with a spica cast [83]. The patients differed significantly with regard to age and weight. The Pavlik harness group had an average age of 3.6 ± 3.8 months (range 1 week to 12 months) vs. 6.5 ± 3.7 months (range 1 week to 12 months) ($p = 0.028$) for the spica cast group. The average weight for patients treated with a Pavlik harness was 5.6 ± 2.1 kg vs. 7.7 ± 3.3 kg ($p = 0.027$) for the spica cast group. All fractures were either spiral or transverse shaft fractures. Average follow-up was very short at 4 weeks. Both groups showed complete healing at their final follow-up appointment. Six (38 %) of the spica cast patients had complications and all were skin-related issues that resolved with local wound care. There were no complications in the Pavlik harness group. These authors surmised that patients up to 1 year of age with femoral shaft fractures were candidates for Pavlik harness treatment. Flynn and Schwend published a review article subsequent to these studies in 2004 and recommended the Pavlik harness as the preferred treatment for patients ≤6 months of age with proximal third or shaft fractures [88].

Very recently, Rush et al. published a retrospective review looking at longer term functional and radiographic outcomes of patients less than 6 months of age with a diaphyseal femur fracture treated in a Pavlik harness [89]. They reviewed 10 patients with an average follow-up of 5.2 years (range 2.6–7.3). The initial age at time of treatment was 2.2 months (range 2.6 weeks to 5.8 months). Patients were treated in a Pavlik harness on average of 43 days and there were no complications reported. Four patients were victims of child abuse. At final follow-up there were no functional deficits, limitations, or complaints noted. There were no clinical angular deformities and there was one patient with an asymptomatic 7 mm leg length discrepancy. The authors did not note whether the affected extremity was long or short. At the time of injury, the average coronal plane deformity was 12° varus (range 0–30°) and sagittal plane deformity was 9° procurvatum (range 0–26°). Average fracture shortening was 2 mm (range 0–7 mm). At final follow-up, coronal plate deformity was, on average, 3° valgus (range 0–8°) and residual sagittal plane deformity was 5° (range 0–24°). The authors noted that the subgroup of patients with >20° of angulation in any plane at the time of injury tended to have larger residual radiographic deformity (5° valgus, 11° procurvatum) present at final follow-up. The authors did not specify how many patients comprised this subgroup. Further, the authors inferred appropriate rotational alignment based on foot progression angles between 5° and 15° external during follow-up gait analysis. The authors concluded that Pavlik harness treatment was safe and effective for diaphyseal femur fractures in this age group but that patients with high levels of initial fracture displacement may need longer term follow-up in case a significant angular deformity persists.

The authors consider Pavlik harness treatment the first option for femoral shaft fractures in patients who will fit in one. This generally lends to a cut-off age around 6 months in full-term infants. This age limit may be higher in a patient who was born pre-term and is still of appropriate size for the harness.

Fitting the Harness

Pavlik harness application is routine for most pediatric orthopedists. However, for the adult orthopedist who finds him/herself in the awkward position of needing to apply the harness, appropriate placement is not too difficult. The centerpiece of the harness is the belt that goes around the lower costal margin. Attached to this are the shoulder straps superiorly and the leg and foot harnesses inferiorly (Fig. 3.2). The harness is placed on a flat surface and unfolded. The infant is placed on top of the harness such that the belt strap lies at the lower aspect of the posterior rib cage. The belt is typically Velcro and is fastened in such a way that the practitioner can easily get two to three fingers under the strap in the anterior chest. This is an easy rule of thumb to follow to prevent applying the belt too tightly. The shoulder straps are generally fastened next. These straps should be firmly secured but not too tightly to prevent skin irritation. Next, the lower extremities are placed in the foot harnesses and secured. There should be about one fingerbreadth of slack in the Velcro straps for the legs. At this point, the fracture is reduced, typically with flexion and external rotation of the extremity, and the straps connecting the foot harnesses to the belt are secured (Fig. 3.3). It should be noted that positioning for fracture reduction should be determined on a case-by-case basis. Early reports depict high levels of flexion to obtain reduction, especially in more proximal fractures [82]. More recent reports tend to recommend hip flexion around 80–90° [83, 89].

Fig. 3.2 Pavlik harness. The centerpiece is the costal/thoracic strap with the shoulder straps above and the leg and foot straps below. Used with permission of the Children's Orthopaedic Center, Los Angeles, CA

Fig. 3.3 Pavlik harness applied to infant. The amount of laxity needed in specific straps is marked to allow the parents to adjust at home if needed. Used with permission of the Children's Orthopaedic Center, Los Angeles, CA

Reduction can be checked during harness application with fluoroscopy, and/or afterward with a conventional radiograph. For the first several days, a pillow or similar soft support is placed underneath the affected extremity to aid in the patient's comfort [83]. A summary of harness application is depicted in Table 3.2.

Generally, the patient should be seen back within a week to 10 days for a follow up X-ray, and any adjustment to the harness can be made at this time if the fracture has lost reduction. The harness should be worn full time for 4–5 weeks and/or until abundant callus formation is seen on the X-ray. Given the massive remodeling potential in this age group, a large amount of displacement can be tolerated.

Table 3.2 Summary and pearls for Pavilic harness application for femur fractures

1. Lay out harness on sturdy but comfortable surface.
2. Lay infant on top of harness.
3. Fasten torso strap first, leave room for two fingers underneath strap.
4. Fasten shoulder straps, leave room for one finger underneath strap.
5. Apply leg strap for unaffected limb. Flex hip to 80–90° and fasten straps.
6. Reduce fracture on affected limb and fasten leg strap in that position.
7. Use X-rays as needed for assistance in reduction.
8. Be wary of hip flexion beyond 90°.
9. Use pillow under hip for several days for comfort.

Like any intervention, there are potential complications with harness treatment. The most notable is femoral nerve palsy [90]. While this has been reported in the developmental hip dysplasia literature, it has not yet been reported in the infantile femur fracture literature. One should still expect this as a possible complication given the low numbers of patients reported in the femur fracture literature. Since pseudoparalysis of the affected extremity is a hallmark finding for femur fractures in this age group, it can be very difficult to get a baseline nerve examination prior to Pavlik harness application and also after several days of harness treatment. Femoral nerve palsy is thought to be associated with higher levels of hip flexion so the practitioner should be mindful of flexing the hip high for a reduction.

Child Abuse

Child abuse is one of the most troubling diagnoses to deal with in the medical profession. In the case of physical abuse, it is often an orthopedic injury that brings the child's diagnosis to the attention of a medical provider. Femur fracture, depending on the source, is often considered the most common long bone fracture to occur in non-accidental trauma (NAT). Determining cases of child abuse from accidental trauma in very young patients can be difficult and requires a multidisciplinary team. Incorrect diagnosis can emotionally scar a family, but missing a diagnosis can be fatal for the child as most patients who die from abuse have a history of previous medical encounters for suspicious injuries.

Epidemiology

In 2011, there were an estimated 681,000 unique child abuse victims, or 9.1 victims per 1000 children in the population [91]. The birth-to-1-year age group represented the highest rate of victimization at 21.2 per 1000 [91]. Boys (49 %) and girls (51 %) are abused at roughly the same rate. Most abuse cases in the U.S. are comprised of three ethnic groups: Caucasian, Hispanic, and African-American, with respective percentages of 44 %, 22 %, and 21.5 % [91]. Given the percentage of each ethnic group in the population, there appears to be a higher rate of abuse among African-American children than Caucasian or Hispanic children [92–94]. Neglect is the most common form of child abuse, accounting for close to 80 % of all cases. Surprisingly, physical abuse only accounts for 20 % of all child abuse cases, and sexual abuse accounted for about 10 %. Based on these percentages, it is clear that some children are victims of more than one type of abuse [91–93]. Four children die from child abuse every day, and this number may be underreported. [91]. Eighty percent of children who die from abuse are under age 4, and 78 % of the time the fatality was caused by one or more parent [91].

There is a strong correlation between long bone fracture in infants and toddlers and child abuse [95, 96]. There is some debate as to whether the femur is the most frequently fractured long bone in this setting, with the humerus and the tibia cited as well [34, 96, 97]. Regardless, a femur fracture is often the injury that brings the battered child to the attention of a healthcare provider. In the infant and toddler age group, the rate of child abuse-associated femoral fracture is anywhere from 10 to 80 % [34, 62, 64–66, 71, 73, 76, 79, 98]. Studies with level II evidence cite a rate of 12–14 % in children aged 0–3 years [71, 73]. In infants who do not yet ambulate, child abuse has been cited to be the cause in up to 60–90 % of femur fractures [52, 66, 75, 95]. Regardless of the exact number, non-accidental trauma is all too common in infants and toddlers, and the practitioner should always be on high alert when these patients present to the emergency department with a femoral fracture. If not recognized, these victims are often beaten repeatedly and death is a very real possibility [77, 99–101]. More than 1500 children each year died from abuse and neglect in 2010 and 2011 [91, 92]. Furthermore, victims of child abuse have higher rates of adult criminal behavior, drug and alcohol abuse, and violent behavior, including being the perpetrators of child abuse [92, 93]. Appropriate recognition and action on the part of the physician can hopefully help minimize this truly disturbing phenomenon.

Presentation

There are several signs that have been put forth in the literature as being suspicious for abuse. The first and easiest thing to look at is patient age. The risk of non-accidental trauma, as stated above, is much higher for children who do not ambulate. Furthermore, based on the statistics discussed above, any infant or toddler with a femur fracture should raise suspicion. To put a final point on this, the AAOS has issued a clinical practice guideline stating that all patients less than 3 years of age with a femur fracture should be evaluated for child abuse [64, 79]. This was the only "Grade A" recommendation from the practice guideline.

Like any thorough work-up, a detailed history is central to steering the physician toward the correct diagnosis. In the setting of abuse, the caregiver will often give an inconsistent story, describe a mechanism of injury that is not plausible, or claim to have not witnessed any injury [76, 77, 93, 99, 100, 102]. Furthermore, elucidating any past injuries or emergency room visits is important, as abuse victims tend to be brought to the hospital on multiple occasions [93, 102]. The past medical history is important to rule out metabolic or structural conditions, such as OI, that predispose children to fracture [33, 103, 104]. While honesty may not be a top priority for a child abuse perpetrator, the social situation should be thoroughly explored to determine if there is drug and alcohol abuse in the home and if the caregivers are of low socioeconomic status. These have been found to be associated with child abuse [52, 77, 91–93, 105].

Type of Fracture

Fractures along the entire length of the femur have been reported in the setting of child abuse [38, 40, 52, 53, 75, 106–109]. A femoral shaft fracture is considered the most common type of femur fracture to present in the setting of child abuse (Fig. 3.4), and likely represents up to 80–90 % of all femur fractures in this setting [75, 96]. The exact type of shaft fracture (spiral, transverse, oblique, etc.) is debated with no clear pattern being most indicative [75, 96, 97, 110]. The shaft fractures have mainly been described in the middle and distal third of the shaft [75, 77, 96, 102]. Twenty percent of shaft fractures may be proximal [77]. Careful X-ray interpretation is important, as there are some lesions that can be mistaken for a fracture that may represent other conditions [102]. Table 3.3 summarizes a differential diagnosis for child abuse.

Fig. 3.4 Solitary oblique mid shaft femur fracture in a 15-month-old female with confirmed child abuse. Used with permission of the Children's Orthopaedic Center, Los Angeles, CA

Table 3.3 Differential diagnosis of child abuse

Accidental injury	*Other*:
Birth trauma	Congenital insensitivity to pain
Osteogenesis imperfecta	Coagulation disorders: • Hemophilia • von Willebrand etc.
Caffey disease	*Normal radiographic variants*:
Rickets	Angulation of ossifying metaphysis
Congenital syphilis	Cortical irregularity
Leukemia	Spurring
	Juxtaphyseal variants

Adapted with permission from Kocher MS and Kasser JR. Orthopaedic Aspects of Child Abuse. JAAOS 2000;8(1):10–20

Imaging

Imaging of NAT follows the same principles as described above for accidental trauma. However, in suspected NAT femoral injuries, a skeletal survey should be ordered [112]. A skeletal survey consists of AP radiographs of all parts of the extremities (e.g. hand, forearm, arm) and AP and lateral X-rays of the axial skeleton and skull. The use of radionuclide imaging has been described to help in detection of associated injuries and to help determine the age of an injury [113–115]. This modality, while useful, may have limitations due to cost, time involvement, and limited availability, but should be considered as an adjunct if abuse is suspected but a skeletal survey is negative [102, 116]. If unavailable, a follow-up skeletal survey can be ordered 2–3 weeks after the initial survey to see if there are healing fractures with associated callus. If there is suspicion for a diagnosis other than child abuse based on initial radiographs, then appropriate imaging (MRI, CT, etc.) and blood work, etc. may be indicated [102].

Associated Injuries

If a child presents to a caregiver with a suspicious femoral fracture (or any injury suggestive of child abuse), a search for other injuries is warranted. Bruises and other skin lesions are the most common finding in child abuse. By looking at the pattern of bruising and the age of the child, the suspicion of child abuse can be tailored appropriately [93]. A general rule of thumb is that if the child is not yet developed enough to cruise, any bruising should warrant suspicion for child abuse [117]. Further, bruising around the thorax, neck, ears, and genitals are suggestive of abuse in any child less than age 4 [118, 119]. Lastly, sharply demarcated bruises or patterned bruising should raise suspicion as well, as this may suggest trauma from an object or restraining device [93, 118].

Fractures are second only to bruises in frequency in the setting of NAT [49, 93, 102, 120]. Long bone fractures are most common, with the humerus and tibia most frequently seen in addition to the femur, as mentioned above [13, 74, 78, 93, 95–97, 100, 102, 110, 120]. While fractures in multiple stages of healing are highly specific for abuse, up to 50 % of battered children present with only a single fracture [96]. Rib fractures alone, especially posterior rib fractures, have been shown to have 95 % positive predictive value (PPV) for child abuse in children less than 3 years of age. In the appropriate setting and history, the PPV for rib fractures goes to 100 % (Fig. 3.5a–c) [93, 102]. Sometimes, the rib fractures are missed on X-ray and can only be detected as the fractures heal and form callus [102, 121]. Other less common fractures in child abuse include the clavicle and hand and foot fractures [102]. As mentioned earlier, corner fractures or CMLs are highly specific for child abuse [111]. In addition to the distal femur, these have been documented on the proximal and distal tibia as well as the distal radius and ulna [96, 97, 102, 106, 122]. Other highly specific fractures for NAT include scapular, spinous process, and sternal fractures [123]. In addition to spinous process fractures, spine fractures typically are asymptomatic vertebral compression fractures that are picked up on skeletal survey. They are also quite rare in NAT but are helpful in diagnostic confirmation since they are also very uncommon as a result of accidental injuries in infants and toddlers [34, 110].

Head injuries are the most frequent cause of long-term morbidity and mortality in NAT and include skull fractures, subdural hematomas, and retinal hemorrhages [93, 102]. The combination of subdural hematomas and rib fractures is known as the “shaken baby syndrome.” Skull fractures that are depressed, bilateral, complex, and/or cross suture lines are associated with abuse (Fig. 3.6). Subdural hematomas that are in the posterior fossa, in multiple locations, or are associated with cerebral edema are also associated with child abuse [93, 124]. Head trauma often leads to long-term neurologic sequelae such as seizure disorders, learning disabilities, delayed development, and motor dysfunction [93, 102, 124].

Other injuries seen in NAT include burns and bites, and are more common than one may first think [93]. Visceral organ injuries are rare, but tend to carry a mortality rate of approximately 40–50 % [125, 126].

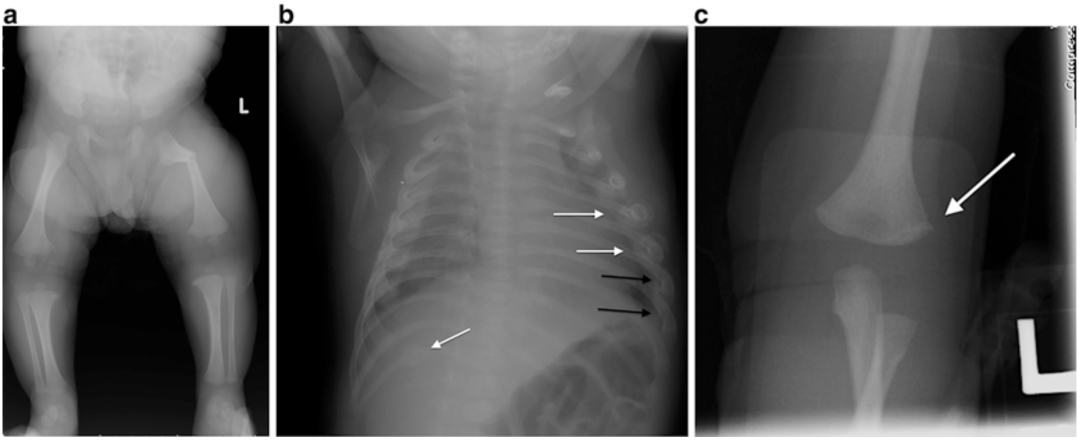

Fig. 3.5 Multiple injuries in a child abuse victim who presented to the ED with a femur fracture. (**a**) Left subtrochanteric femur fracture. (**b**) Multiple rib fractures in various stages of healing. The *black arrows* point to more recent fractures and the *white arrows* point to fractures with abundant callus. (**c**) Small, healed lateral distal humeral corner fracture. Used with permission of the Children's Orthopaedic Center, Los Angeles, CA

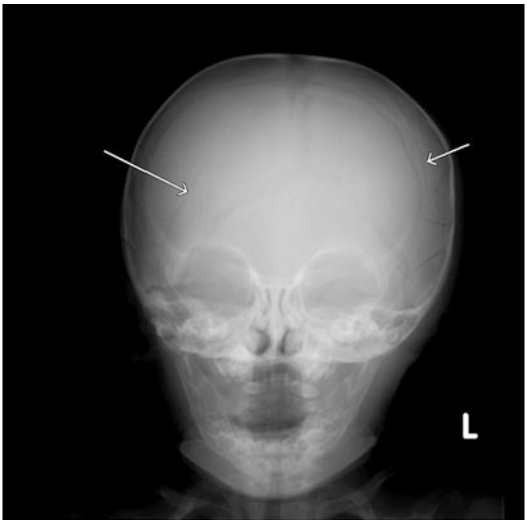

Fig. 3.6 Bilateral skull fractures in an abused child. Used with permission of the Children's Orthopaedic Center, Los Angeles, CA

Risk Factors for NAT

When evaluating a child with a femoral fracture for child abuse, the clinician should assess the presence of associated risk factors. Baldwin et al. evaluated a series of femur fractures in patients younger than 4 years of age. They determined risk factors of a suspicious history, radiographic evidence of prior injury, and age less than 18 months to be significant risk factors for abuse. When no risk factor was present, the risk of abuse was 4 %. When one, two, or three risk factors were present, the risk climbed to 29 %, 87 %, and 92 %, respectively [77]. Other risk factors noted in the literature include low socioeconomic status [91–93], being on Medicaid insurance or being uninsured [52], single-parent households or having a partner in the house who is not a parent [92], drug and alcohol abuse in the caregivers [91, 92], multiple trips to the ED [93, 100], delay in presentation [76, 93, 100], associated injuries [76, 93, 100, 102], and children with special needs (Table 3.4) [102].

Treatment

Treatment of femoral fractures in the setting of child abuse follows the same principles as treating accidental trauma discussed above. Often, the battered child will have more than one injury, so a multidisciplinary team is needed to provide comprehensive care as well as arrange a safe disposition for the child after he/she leaves the hospital. As a general rule, no child less than age 2 with a femur fracture should be discharged from the hospital without a further investigation. Social Services consult is mandatory in the setting of abuse or

Table 3.4 Risk factors for child abuse when evaluating a femur fracture in a child

• Suspicious or inconsistent story
• Delay in presentation
• Implausible mechanism of injury
• Multiple trips to ED
• Low socioeconomic status
• Government insurance or no insurance
• Single-parent household or live-in non-parent partner
• Drug and/or alcohol abuse in caregivers
• Fracture in child less than 3–4 years
• Fractures in multiple stages of healing
• Presence of highly specific fractures
– Posterior rib
– Corner fractures
– Scapula
– Spinous process
• Associated injuries
– Bruises: thorax, neck, ears, genitals
– Burns
– Skull fracture
– Retinal hemorrhage
– Subdural hematoma
– Visceral injury (uncommon)

suspected abuse. The resources and expertise of Social Services are much more extensive than a practicing surgeons' and should be used given the complexity of issues such as investigation into the social scenario as well as potential placement issues.

Conclusions

Femoral fractures in the infant and toddler are generally well tolerated, but attention to detail will help to ensure good outcomes. There are unique aspects and considerations for these patients based on their mechanism of injury, stage of development, and home surroundings. Non-operative care is standard, and the Pavlik harness has made neonata and infantile fracture treatment more convenient for parents and caregivers alike.

Child abuse is a disturbing and unfortunate reality in this age group, and physicians and other healthcare workers must act as a team to diagnosis, treat, and protect these children. By the time the diagnosis is made, physical and psychological long-term damage may already be done, but we must do our best to minimize ongoing or further injury to these children.

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Femoral Head Fractures in Children

4

Peter D. Fabricant, Bryan T. Kelly,
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Introduction

Femoral head fractures in children are exceedingly rare. The overall incidence of hip fractures in children account for less than 1 % of pediatric fractures [1], with Delbet Type I femoral head fractures accounting for only 8 % of these [2]. Given their rarity, a pediatric orthopedic surgeon at a level-1 pediatric trauma center may encounter anywhere from none to several in an entire career. However, due to the high morbidity that may be associated with the injury, understanding the underlying principles and advance preparation for the technical challenges is critical to ensuring the best possible outcomes for children. The rarity of the injury has precluded large prospective studies to date; rather, reports on the topic have been limited to small retrospective case series. One exception is slipped capital femoral epiphysis (SCFE), which is more common but a distinct entity from acute traumatic femoral head fracture, in that it results from chronic repetitive microtrauma, although SCFE occasionally manifests itself in an "acute-on-chronic" fashion. Few authors categorize the entity in the realm of femur fractures, and SCFE will therefore not be discussed here.

Femoral head fractures have a high complication rate with potentially devastating consequences, including avascular necrosis (AVN) and proximal femoral deformity, especially when diagnosis and treatment are missed or delayed. This chapter will discuss both epiphyseal and transphyseal femoral head fractures, and provide diagnostic tips, a treatment algorithm, and reported clinical outcomes and complications.

Anatomy of the Femoral Head

Femoral head fractures in children are defined as those that take place at the level of, or superior to, the physeal plate. According to the Delbet classification (Fig. 4.1), these represent the array of Delbet Type I fractures. In securing diagnoses and formulating treatment plans, it is vital to understand the anatomy of the femoral head. While the development and growth of the pediatric femur is covered elsewhere in this book, we will perform a brief review of the vascularity and anatomical principles relevant to femoral head fractures.

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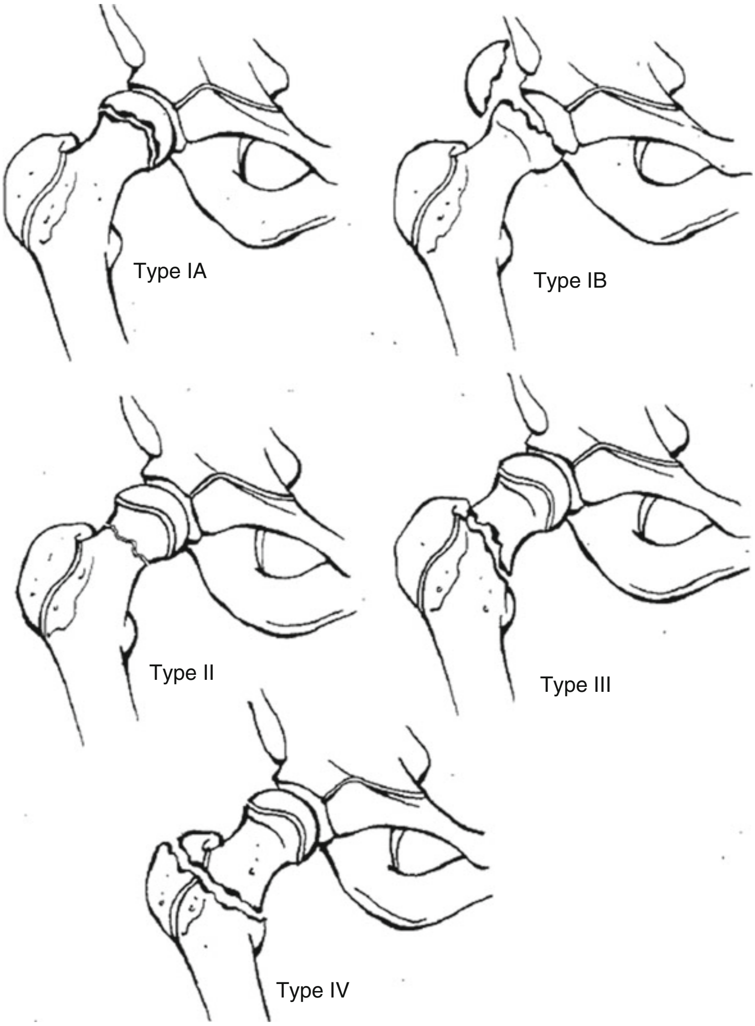

Fig. 4.1 Delbet classification of hip fractures in children. I, transepiphyseal with (IB) or without (IA) dislocation from the acetabulum; II, transcervical; III, cervicotrochanteric; and IV, intertrochanteric. Adapted from Flynn, JM, and Skaggs, DL. In: Rockwood and Wilkins' Fractures in Children. Philadelphia: Wolters Kluwer Health; 2014. Figure 26-3 [38]

Anatomical restoration of the articular cartilage and subchondral bone of the femoral head is vital to successful treatment. The vascular anatomy is of paramount importance, as avascular necrosis (AVN) is one of the most feared complications of femoral head fractures, leading to consistently poor outcomes.

The lateral epiphyseal vessels supply the majority of the developing femoral head, and are tributaries of the ascending cervical branches of the medial femoral circumflex artery (MFCA). At the level of the intertrochanteric groove, the ascending vessels penetrate the hip capsule deep to the gemelli and obturator internus tendons and course in the soft tissue on the lateral femoral neck. The vessels penetrate the epiphysis of femoral head proximal to the lateral physis [3–5]. While the lateral femoral circumflex artery (LFCA) does in fact nourish the anterior femoral head, this is largely absent by age 2 or 3, at which time it is the principle supply of the femoral neck metaphysis. With the development of the physis at age 14–18 months, this metaphyseal blood supply is prevented from providing direct access to the femoral head [4], and only may be restored after complete physeal closure occurs. The majority of the femoral head blood supply still comes from branches of the lateral retinacular vessels and the medial vessels found in the ligament of Weitbrecht [3, 6]. The artery of the ligamentum teres, a branch of the obturator artery, provides minimal blood supply to the femoral head and is typically not sufficient to maintain appropriate metabolism of the articular cartilage and subchondral bone. Therefore, in the face of displaced femoral head fractures, anatomic reduction is critical to optimizing revascularization of the femoral head via the vasculature of the lateral head and neck, the future health of which may ultimately be compromised even in the best technical result.

Diagnosis

The diagnosis of femoral head fracture in children is confirmed with a thorough history, physical examination, and, perhaps most importantly, appropriate imaging studies. While it is not typically a concern in low-energy injury, femoral head fracture may be missed in high-energy trauma due to distracting concomitant injury. It should be ruled out in every case of high-energy lower extremity trauma, hip dislocation, and acetabular or pelvic fracture. Focused history should include a description of the mechanism of injury, previous hip injury, or antecedent hip pain or limping. After primary survey and initial stabilization from associated injuries, physical examination should include a complete musculoskeletal assessment, especially a detailed examination of the entire affected limb. Children with intracapsular hip fractures prefer to lie with the limb flexed and externally rotated, to maximize the volume of the hip joint to accommodate the resultant hemarthrosis. Any range of motion will likely be very painful. Range of motion may reveal the presence of crepitus or blocks to motion. Hip pain or referred pain to the knee with straight leg raise or logroll should raise suspicion of hip injury. A careful neurovascular examination should be documented, with attempted distal strength testing in children and adolescents old enough to cooperate with careful motor and sensory examination.

Radiographic diagnosis is essential, as many physical examination findings in this age group are nonspecific. Anteroposterior (AP) pelvis and AP and cross-table lateral views of the affected hip are performed first, with careful attention paid to joint congruity. Full-length femur radiographs should also be obtained to rule out associated femoral shaft or distal femoral injury. Frog-lateral images are avoided due to the potential for fracture displacement; cross-table lateral imaging is preferred if pain allows. If there is a loose chondral or osteochondral fragment in the hip joint, femoroacetabular congruity may be compromised even if the fragment is radiolucent. An occult fracture may be present in children presenting with a hip dislocation. This is best detected with a high-quality fluoroscopic examination both prior to, and during, any attempted reduction to detect subtle incongruity of the femoral head–metaphyseal junction [7]. If not recognized, frank transphyseal separation may occur during reduction, displacing the epiphysis, and increasing the risk of complications and poor outcome [8]. Therefore, if a nondisplaced or minimally displaced femoral head or femoral neck fracture is seen in association with a dislocated hip, we recommend against an attempted reduction in the emergency room under sedation, even if fluoroscopic assistance is available. Instead, a reduction in the operating room is favored, often with an open approach to prevent head or neck displacement in the act of reduction. Larger Delbet Type I osteochondral fragments may be obvious on plain radiographs. CT scan can help characterize osseous architecture, joint congruity, and trauma, as well as associated pelvic trauma, and three-dimensional reconstructions can greatly assist with surgical planning. However, prior to closure of the triradiate cartilage, MRI should be used for cross-sectional imaging of the hip and pelvis, as CT scan may miss injury to those structures that have not yet ossified such as the posterior acetabular wall [9]. If possible, urgent MRI should be obtained if there are any positive plain radiographic findings or a high index of suspicion. MRI is also a valuable radiographic tool in characterizing small chondral or osteochondral fractures of the femoral head in older children that may not be well defined on plain radiography or CT scan.

Transphyseal Fractures

Fractures of the proximal femur are considered urgent cases, and should be treated with reduction, joint decompression, and fixation within 24 h of injury [10, 11]. Delay greater than 24 h has been shown in meta-analysis to increase the rate of AVN by 4.2× [12]. Associated injuries such as head and facial trauma, abdominal, and thoracic injury can be seen in up to 85 % of cases [13] and should be managed expeditiously in order to minimize treatment delays. While definitive treatment within 6 h is recommended for hip dislocations in order to minimize risk of AVN [14, 15], there are no studies that have shown improved outcomes from treatment of proximal femur fractures within 6 h, though this may be a product of inadequate sample sizes or methodology of prior studies. Treatment within 24 h is considered standard of care [12]. Evacuation of intracapsular hematoma is postulated to minimize the risk of AVN [11, 16], however this remains controversial as neither large clinical studies nor meta-analysis of smaller studies [12] have shown a distinct advantage [12].

Pragmatically, clinical practice suggests that urgent treatment with joint decompression, closed or open anatomic reduction, and stable fixation should be done as soon as possible when the patient is stabilized, and by a surgeon who is technically comfortable with the procedure given the highly technical nature of the operation and potential for injury-related complications.

Physeal separation and large fragment Delbet Type I fractures typically result from high-energy trauma, and the orthopedic surgeon must be vigilant in evaluating for associated injuries. The femoral epiphysis may or may not be dislocated from the acetabulum, which differentiates Delbet Type IA (not dislocated) from Delbet Type IB (dislocated). Both types are equally common after high-energy trauma [17]. Because of the high energy required to cause physeal separation or transepiphyseal fracture, child abuse should be suspected if the presenting patient is an infant or toddler without an obvious mechanism of injury. In older adolescents, these fractures may be an acute variant of slipped capital femoral epiphysis (SCFE), which may present in the setting of a lower-energy mechanism. Outcomes from Delbet Type I fractures are frequently suboptimal due to the high rates of one of the following three complications: (1) AVN, (2) premature physeal closure, or (3) nonunion. Treatment options include closed reduction with internal fixation for minimally or non-displaced fractures and in rare instances in fractures with displacement where anatomic reduction can be done closed. Open reduction and internal fixation is needed for displaced fractures where reduction cannot be obtained for closed or dislocated fractures.

Newborns who sustain physeal separation resulting from aggressive obstetrical maneuvering during birth typically have excellent outcomes without AVN despite frequent delay in diagnosis and treatment. In the series of six cases described by Theodorou et al., radiographs in these newborns had revealed proximal displacement of the femur after difficult deliveries, with varying, but overall minimal treatments pursued, such as simple placement abduction or gentle traction [18]. All patients showed abundant callous and ultimately normal hips. Based on these limited data, Pavlik harness placement with ultrasound follow-up to assess femoral head–neck position likely represents the optimal treatment approach. Minimally displaced stable fractures in young children (e.g. <2–4 years old) may be treated with spica casting [17, 19], and have a good prognosis with nonoperative management [19]. In older children, for those Delbet Type I fractures that are contained within the acetabulum, closed reduction with internal fixation may be first attempted, provided there appears to be an anatomic reduction. This is performed on a flat radiolucent table, though children who are large enough (typically starting in early adolescence) may be better suited for operative fixation on a hip fracture table, depending on surgeon preference. Closed reduction is performed with the patient supine, pulling longitudinal traction and internal rotation distally with the hip in extension and abduction. Consideration may be given to utilizing two image intensifiers simultaneously, such that AP and lateral fluoroscopic views may be taken in immediate succession, without manipulation of the patient or image intensifier while performing closed reduction and applying implants. If anatomic reduction can be obtained by closed methods, we prefer not to perform open reduction. However, repeated attempts at closed reduction should not be performed and there should be a low threshold to convert to open reduction. When open reduction is necessary, an anterior/posterior or surgical dislocation approach is chosen, based on surgeon experience and comfort. In addition to more precise control of the femoral head, open reduction via a surgical hip dislocation approach allows the surgeon to evaluate the periosteal sleeve to assure it is not strangulated, and subsequently take all necessary means to decrease the high likelihood of AVN. This is of paramount importance during patient and family discussions postoperatively.

Once reduced, implants are chosen based on the child's age and growth remaining: 1.6 mm smooth wires are preferred in children under 3 years old, 1.6 or 2.0 mm smooth wires or 4.5 or 6.5 mm cannulated screws for those ages 4–10 years old, and 6.5 or 7.3 mm cannulated screws for children older than 10 years old, with adjustments made according to the size of the child. Because implants necessarily pass across the physis with these fractures, smooth wires are preferred whenever possible, but maintenance of reduction should be prioritized over maintenance of physeal integrity. This preference is based on the concept that premature physeal closure and subsequent leg length discrepancy represents a better tolerated and more easily treated complication than loss of reduction or AVN. Children under 10 are almost universally protected with a hip spica cast for 6–8 weeks as well [17].

In cases of closed reduction and internal fixation of Delbet Type I femoral head fractures, we prefer to routinely perform capsular decompression with a scalpel via the lateral surgical wound after screw placement. We do not use a periosteal elevator as we feel that it is too blunt to effectively create a sufficient capsulotomy, and prefer to incise the tissue in a controlled fashion rather than attempt to bluntly strip it off the bone. Alternatively, the hematoma may be decompressed with a large-bore spinal needle under fluoroscopic guidance either anteriorly or medially with a subadductor approach. Although no large clinical studies have proven a relative benefit to capsular decompression for these fractures, some case series' authors have advocated for its use [11, 20, 21]. Moreover, in vitro studies of children with unstable SCFE have shown a tamponade effect of intracapsular blood, with pressures reaching 75 mmHg after closed manipulation [22]. While the rarity of femoral head fractures makes comparative studies difficult and likely underpowered to show any difference in rates of AVN [12], this treatment algorithm has been reported to confer a decreased risk of AVN in the treatment of unstable SCFE in the clinical setting [5, 10, 16, 23].

For non-reducible fragments, non-anatomic reductions, or dislocated (Delbet IB) fractures, open reduction and internal fixation is required. Also, primary open reduction and internal fixation should be performed for suspected or occult fractures in the setting of a hip dislocation [7]. Some have advocated for curettage of the physeal plate at the time of ORIF in order to enhance revascularization of the femoral head, however this technique has only been formally proposed in one small case series [8]. Surgical approach should be dictated by the direction of fragment dislocation. In the event that the fragment is dislocated anteriorly, an anterior (Smith-Petersen) approach is used, while a posterior (Kocher-Langenbeck) approach is reserved for posterior fragment dislocation. Alternatively, whenever feasible we prefer to approach most instances of Delbet Type IB fractures by utilizing an anterior capsulotomy and surgical hip dislocation, as described by Ganz et al. [24], which is performed through a lateral incision and trochanteric flip osteotomy. This allows for circumferential exposure of the femoral head and acetabulum as well as preservation and observation of remaining femoral head blood supply. The femoral head can then be retrieved via the traumatic path through which it travelled. We prefer to carry out the Gibson modification [25], in order to minimize bleeding from branches of the inferior gluteal artery and prevent denervation of muscle from the inferior gluteal nerve. A z-shaped capsulotomy is made, through which the femoral head and neck may be delivered and inspected circumferentially. After complete exposure, the fragment may be reduced and rigidly fixed, either with retrograde screws or smooth wires as described above. During closure, two 3.5 mm cortical screws are used for fixation of the trochanteric osteotomy.

Postoperatively, anterior hip dislocation precautions (limiting hip extension and external rotation), trochanteric hip precautions (limited active abduction and passive adduction), and foot-flat touch-down (30 %) weight bearing with crutches are maintained for 8 weeks. In older children and adolescents, anti-embolic stockings, sequential lower extremity compression devices, and early mobilization are encouraged to prevent deep venous thrombosis (DVT). After 8 weeks, if radiographs indicate fracture healing, weight bearing is progressed as tolerated, with full return to activities largely dependent on symptomatology. Screw removal is performed at the discretion of the treating surgeon, and is not universally performed in our practice. Patients are followed clinically and radiographically until skeletal maturity. While Yeranosian et al. reported that 40 % of Delbet Type IB femoral head fractures will progress to AVN [12], most experts expect this to occur in the vast majority of cases. Therefore, patients and families should be counseled accordingly, such that realistic expectations are set with regard to functional outcomes and the potential need for future treatment.

Epiphyseal Fractures

Chondral and osteochondral fractures of the proximal femoral epiphysis are varied, and range from small subcentimeter cartilage fragments to large osteochondral fragments resulting from high-energy trauma and/or hip dislocation. Fragment size and displacement are the main determinants of treatment strategy.

Fragments comprising a large portion of the epiphysis are treated using the same criteria as transphyseal fractures, as described above. Small osteochondral fractures in younger children are less frequent due to the pliability of young bone, and those that are nondisplaced may be managed nonoperatively or in a spica cast. As children approach adolescence, operative fixation is favored for larger fractures with osseous injury. Typically, small chondral and osteochondral fractures are the result of an impaction mechanism and/or epiphyseal injury during reduction of a hip dislocation. Very small, mostly cartilaginous, injuries in non-weight bearing regions (parafovial) may be observed and treated with arthroscopic removal later if symptomatic or if they result in a non-concentric reduction in the event of traumatic hip dislocation. Larger fractures, particularly in the weight-bearing portion of the femoral head, are treated using an open surgical hip dislocation, as described above. After surgically dislocating the hip, the fracture fragment and fracture bed may be precisely prepared, reduced, and fixed using implants selected based on the fragment size. Small cartilaginous fragments are repaired using bioabsorbable chondral tacks or darts. Larger osteochondral fragments are fixed using subchondral tacks or darts or buried headless compression screws. An anterior or posterior approach may also be utilized in those without experience in the surgical hip dislocation technique.

Arthroscopic Treatment

Currently there are no data to suggest that arthroscopic management of femoral head fractures in the pediatric population is a preferred method of treatment. We therefore do not perform arthroscopic fixation of osteochondral fragments at this time. Small osteochondral fragments and those around the fovea that are not weight bearing may be excised arthroscopically if they are symptomatic. An acetabular rim osteochondral fragment after a hip dislocation may be treated by an experienced hip arthroscopist. In the majority of cases of femoral head fracture fixation, we prefer an open surgical dislocation approach. This allows for 360-degree visualization of the femoral head, precise reduction of osteochondral fragments, and rigid fixation tangential to the fracture line. While one case of arthroscopic reduction and internal fixation of small femoral head fracture has been reported in a skeletally mature patient [26], we feel that obtaining tangential fracture fixation via the arthroscope is technically challenging, even in the hands of an experienced arthroscopist. Furthermore, cases of intraabdominal fluid extravasation have been reported after loose body removal [27–29], including one case of cardiac arrest after fluid extravasated through an acetabular fracture [30]. Given these potential risks, and inferior access to fracture reduction and fixation, we prefer treating surgically indicated femoral head fractures via an open surgical dislocation approach.

Outcomes and Complications

Clinical outcomes after femoral head fractures are varied. In isolated cases that are treated expeditiously and do not develop AVN, a good outcome can be expected. In a recent systematic review and meta-analysis [12], data aggregated from 13 studies reported that children with Delbet Type I femoral head fractures had very limited outcomes. Only 30 % of subjects were rated as "good" by Ratliff's criteria [31], which corresponds to those children with no pain, full range of motion, normal activity, and no or minimal proximal femoral deformity. Eleven percent noted "fair" outcome, with the majority (59 %) having "poor" clinical outcome by Ratliff's criteria, corresponding to disabling pain, range of motion <50 % of the contralateral side, restricted activity, and radiological signs of AVN, arthrosis, or arthrodesis. Delbet Type I fractures had the poorest outcomes when compared to Types II, III, and IV. Of note, often poor functional outcomes in these children are compounded by, or a direct result of, associated injuries such as traumatic brain injury [32] in addition to hip pathology.

Table 4.1 Rate of complications after Delbet Type I femoral head fractures[a]

Outcome	Percent (%) of children	Number of studies reported
Avascular necrosis	40	27
Growth arrest	49	19
Revision surgery	39	9
Coxa vara	32	22
Infection	22	9
Nonunion	6	23

[a]Adapted from pooled data used in meta-analysis by Yeranosian et al. [12]

Complication rates after femoral head fracture in children are detailed in Table 4.1. The most common reported complication is AVN, which has been shown in meta-analysis to occur in 40 % of cases of Delbet Type I fractures, the highest rate among all types of pediatric hip fractures [12]. This corresponds to 14.5× odds for developing AVN than those children who sustain Delbet Type IV (intertrochanteric) fractures [2]. Fragment displacement is a critical risk factor for development of AVN. Particularly for those who sustain a dislocated epiphysis (Type IB), the risk of AVN approaches 100 %.

In addition to AVN, other commonly reported complications from meta-analysis of studies published between 1960 and 2011 include proximal femoral growth arrest (49 % of subjects from 19 studies), coxa vara (32 % of subjects from 22 studies), infection (22 % of subjects from 9 studies), and nonunion (6 % of subjects from 23 studies, all of which lead to revision surgery in 39 % of cases as assessed from 9 studies) [12]. Studies comparing outcomes or complication rates after operative vs. non-operative treatment have little value in that these cohorts likely represent a different spectrum of injury severity.

Treatment of Late Sequelae

Avascular necrosis is a common complication of femoral head fractures in children, and is nearly universal in Delbet Type IB fracture-dislocations. Late treatment options for AVN include core decompression, vascularized fibula autograft, hip osteotomies, hip fusion, and total hip replacement. None of these treatment options is associated with consistently good functional outcomes, given the fact that young children and adolescents often require multiple revision surgeries over the course of their lifetime. While not well studied in this population, given the nearly universal progression of hips to AVN and femoral head collapse after Delbet Type IB fracture-dislocations, there may be a role for single-stage open reduction and internal fixation with concomitant core decompression and vascularized fibula autograft, or short-interval two-stage combination procedures [33–36].

Focal chondral or osteochondral impaction or crush injuries may result from hip dislocation/relocation events, and can be difficult to fix primarily, thereby warranting later reconstruction or resurfacing techniques. Such techniques may also have a role following failed ORIF of small chondral or osteochondral fragments. We favor a surgical hip dislocation for these techniques. After exposure of the femoral head, the defect size and shape is evaluated. Small irregularly shaped defects may be treated with mosaicplasty using an osteoarticular transfer system with either autograft tissue from the ipsilateral knee, or allograft plugs from a size-matched cadaver [37]. For larger defects, an osteochondral allograft may be used from a size-matched donor using a dowel technique. To perform this, the defect is sized and oriented over a guide pin placed centrally in the lesion tangential to the curvature of the femoral head. The defect is excised by reaming over the guide wire to an appropriate depth. A size-matched cadaveric femoral head is utilized as donor tissue, and a core of intact bone and cartilage is harvested and fashioned to match the recipient site in both surface area and depth, and is impacted into place. An interference fit eliminates the necessity for additional internal fixation. After restoration of the femoral head, the hip joint is reduced and brought through a physiologic range of motion, ensuring unobstructed motion without crepitus. Because this technique has the potential for physeal damage and is performed after the development of localized osteochondral defect, it is typically reserved for older children and adolescents.

Conclusion

Femoral head fractures in children carry a guarded prognosis, largely due to a high rate of AVN and concurrent injuries sustained during high-energy trauma. Fortunately, they are extremely rare, and account for only 0.08 % of fractures in children. Prompt diagnosis and timely (within 24 h) capsular decompression, reduction, and internal fixation likely offer the child the greatest chance of a good outcome. Stable, anatomic fracture fixation with minimal disruption of blood supply is ideal, sometimes at the expense of physeal integrity, due to the need for transphyseal screws. Currently, there are no well-established indications for arthroscopic treatment of pediatric femoral head fracture, regardless of fragment size. Given the high rate of complications in these patients, patients should be followed through skeletal maturity, and counseling the family on expected outcomes and further treatment of late sequelae is of paramount importance.

Case Example

A 15-year-old female who was a restrained passenger in the back seat of a car during a motor vehicle collision sustained a Delbet Type IB fracture-dislocation. Injury radiographs revealed a dislocated femoral head (Fig. 4.2a), which was superior and posterior to the acetabulum (Fig. 4.2b). Treatment consisted of emergent open reduction via a posterior (Kocher-Langenbeck) approach, and internal fixation using anterograde partially threaded screws (Fig. 4.2c). The patient went on to AVN with femoral head collapse within 1 year of her injury, failed a vascularized fibular autograft (Fig. 4.2d), and underwent total hip arthroplasty at age 19 (Fig. 4.2e).

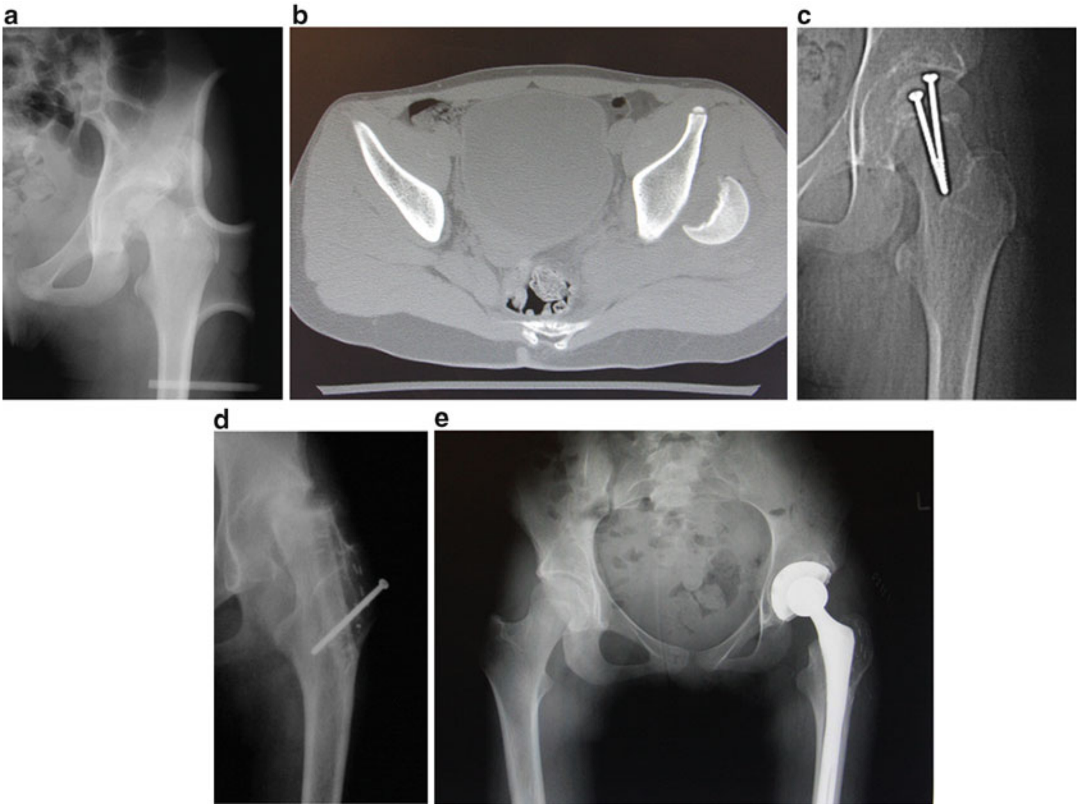

Fig. 4.2 (**a–e**) Case Example: A 15-year-old female restrained passenger in the back seat of a car sustained a motor vehicle collision. (**a**) Injury radiographs reveal a Delbet IB fracture-dislocation, with (**b**) the epiphysis displaced superior and posterior to the acetabulum. (**c**) Fracture open reduction and internal fixation was performed using anterograde partially threaded screws. (**d**) Vascularized fibular autograft was performed for early AVN, however after development of end-stage arthritis the patient underwent (**e**) total hip arthroplasty at age 19. Case courtesy of Mark A. Seeley, MD, Frances A. Farley, MD, and Michelle S. Caird, MD

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Fractures of the Femoral Neck in Children

5

Jaime A. Gomez, Benjamin J. Shore, and M. Timothy Hresko

Introduction

Femoral neck fractures are fortunately uncommon in children. Overall femur fractures account for 2.3 % of children's fractures, however femoral neck fracture account for less than <1 % [1]. The majority of femoral neck fractures occur secondary to high-energy mechanisms and it is unclear if the incidence of this injury has changed in the last decade, since no specific epidemiological studies have been published. According to the most recent pediatric epidemiology studies, fracture incidence appears to have decreased in the last few decades secondary to less physical activity, improved protective equipment, and increased traffic safety [2, 3]. However, this is unclear, as other studies have shown an increased overall fracture incidence which may be related to increased motor vehicle speeds and increased participation in contact sports [4].

Femoral neck fractures are usually seen in patients after high-energy trauma (i.e. motor vehicle accidents), but pathologic and stress fractures may occur after lower-energy trauma or repetitive impact activities, and one must also be aware of these clinical scenarios in the setting of hip pain in the adolescent patient. Significant complex long-term morbidity can be generated from the injury and/or the treatment of a femoral neck fracture in a child; for this reason, these fractures require sharp recognition and careful examination. The major complication of this injury is due to the tenuous blood supply of the femoral head leading to a high incidence of osteonecrosis (ON). In the presence of an open physis malunion, nonunion, delayed union, coxa vara, or growth abnormalities can occur after treatment of femoral neck fractures. Development of ON significantly impacts long-term functional outcomes in this population, so efforts to minimize this complication need to be employed. Thus, diminishing the risks of ON and all other complications during treatment of femoral neck fractures in children is of paramount importance to improve functional outcomes.

Clinical Presentation

Femoral neck fractures in children commonly occur after high-energy trauma and adherence to pediatric ATLS protocols must occur during all

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Fig. 5.1 Clinical photograph demonstrating Pediatric Bucks Traction

trauma scenarios. During the musculoskeletal survey, the orthopedic surgeon or emergency medicine physician must suspect a femoral neck fracture when the child is unable to weight bear on the affected lower extremity and presents with a shortened and/or externally rotated limb. Detailed neurovascular evaluation must be performed for all trauma patients; however, in the setting of an open fracture or associated hip dislocation, high suspicion of neurovascular injury must be suspected. Ankle brachial index (ABI) measurements should be obtained when pulses are equivocal, by measuring systolic blood pressure in one upper extremity and comparing that with the ankle systolic blood pressure. An ABI of <0.9 will mandate further vascular assessment with a vascular surgeon consult and/or advanced imaging. Historically, conventional radiology suite arteriography or surgeon-performed arteriography in the emergency or operating room has been used to evaluate such patients. In recent years, advances have included the introduction of mobile digital subtraction angiography (DSA) in the trauma resuscitation room and multi-detector computed tomography arteriography (MDCTA) [5]. Ipsilateral pelvis, knee, and ankle evaluation should be performed when a femoral neck fracture is detected because of the potential associated injury with a femoral neck fracture.

Patients will present with painful range of motion (ROM) and a positive log roll test on the affected hip. Multiple examinations and manipulation of the fractured hip should be avoided to decrease the risk of further fracture displacement. Upon presentation some of the patients will present with immobilization devices; these should be promptly removed in the emergency room because of the significant risk for skin sloughing over the dorsum of the ankle, and pressure over the sciatic nerve [6]. The patient's limb should be immobilized, and the preferred method for this is with the use of "Bucks" skin traction immobilization with 10 % body-weight traction with a maximum weight of 10 pounds (Fig. 5.1). Alternative immobilization with the use of a posterior splint from the ilium to the ankle will also facilitate easier mobilization, improve pain control, and limit the risk of further fracture displacement. However, skin traction immobilization has demonstrated superior pain control in the setting of femur fractures compared to simple splinting [7]. Readily available skin traction kits allow for gentle traction/immobilization or can be done in the emergency room with ace wrap and Coban (3M™ Self-Adherent wrap), being careful to avoid significant traction over the skin that can increase soft tissue problems.

In the initial hospital setting, it is prudent to counsel parents and patients regarding the potential risk and consequences of the injury and its treatment [8]. Early parent education on the potential risk of ON and need for further treatment will help generate expectations regarding the potential complications associated with this injury.

Relevant Surgical Anatomy

The anatomy of the proximal femur has been reported in multiple studies [9–11]. Blood flow to the femoral head is mainly supplied by the retinacular branches (posterosuperior and posteroinferior) of the medial femoral circumflex artery (MFCA). The lateral femoral circumflex artery (LFCA) contributes blood flow to the greater trochanter, small areas of the medial physis, and the anteromedial metaphysis. The artery of the ligamentum teres and the LFCA begin a process of regression after 4 years of age that is completed by age 10. During this period the MFCA progressively becomes the predominant nutrient provider. The end arterial blood flow of the posterosuperior retinacular branch supplies the anterior and lateral femoral head and is the main contributor to femoral head blood flow until skeletal maturity [9]. The exact location of the main vessels is of significant importance when approaching the hip and performing a capsulotomy. It is believed that an anterior capsulotomy avoiding the superolateral ascending branches will not damage the blood supply to the femoral head, as proposed by Ganz et al. [12].

The higher risk of ON after a femoral neck fracture in a growing child can be attributed to the tenuous blood supply illustrated above. At skeletal maturity the retinacular, ligamentum teres, and metaphyseal vessels establish a definitive anastomotic system that improves femoral head circulation and decreases the risk for ON in adults with femoral neck fractures [13]. Proximal femur development is also important to understand when facing a femoral neck fracture. The proximal femoral epiphysis begins to ossify at age 4–6 months in females and at age 5–7 months in males. The trochanteric apophysis begins to ossify at age 4 years. The fusion of the trochanteric apophysis and the femoral epyphysis occurs at age 14 in girls and 16 in boys [14]. Injury to these regions due to the initial trauma or subsequent osteonecrosis potentially may result in a growth disturbance.

Diagnostic Imaging

Diagnostic imaging should always begin with an anteroposterior (AP) pelvic radiograph. The AP pelvis should be obtained with the hips extended and internally rotated (15°) as tolerated by the patient. This view will serve as a comparative view with the contralateral side to assess displacement. The lateral view should be obtained with a cross-table technique to avoid displacement and increased pain with the mobilization of the injured limb required for a frog-leg lateral film. For completion of skeletal assessment, an AP of the femur and lateral radiographs should be obtained.

In the very young child under 2 years of age, ultrasound can be useful to evaluate for occult fractures in a child with post-traumatic hip pain where standard plain films are non-conclusive. An expert radiologist and technician can evaluate the proximal femur with ultrasonography and clear signs of fracture can be found in up to 92 % of confirmed occult fractures, as per previous reports [15]. Ultrasound findings include cortical discontinuity (direct sign of a fracture), epiphyseal mobility, step-off deformities, tiny avulsed bone fragments, double-line appearance of cortical margins, and diffuse irregularity of bone surfaces [15].

Femoral Neck Stress Fractures

Stress fractures of the femoral neck can be difficult to diagnose on plain radiography alone, but important to treat since they carry a risk of becoming complete fractures and subsequently displacing. Although the prevalence in the pediatric population is fortunately infrequent, some patient populations require discussion. Specifically in patients with the female athlete triad (eating disorder, amenorrhea, and decreased bone mineral density), a thorough workup should be undertaken to avoid missing these injuries in a patient with hip pain [16, 17]. When regular X-rays are not diagnostic, the clinician should remain suspicious, and further imaging with a CT scan has been used in the past. This imaging modality will give an excellent outline of the bony anatomy, but could miss an injury that only generates bony edema. For this reason, MRI is preferred for the evaluation of an occult fracture. A linear dark line will be present in all sequences if a fracture is present, and the surrounding marrow edema will be more noticeable in T2 sequences even within the first 24 h after injury. Recently, an algorithm has been proposed for the

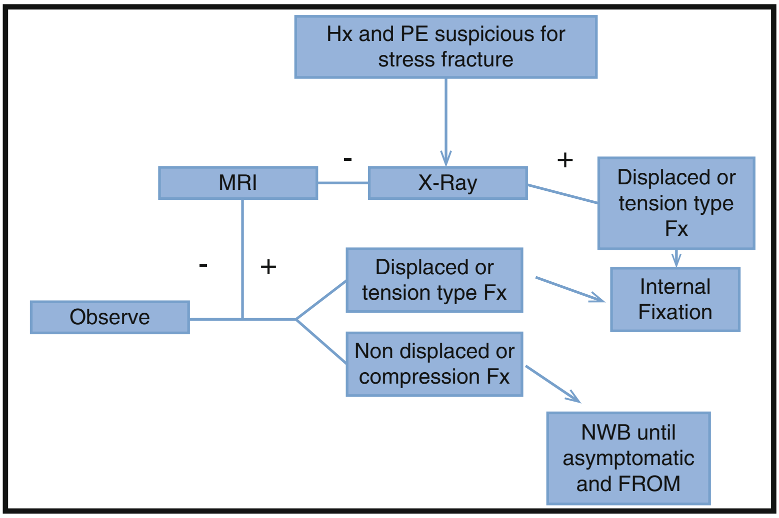

Fig. 5.2 Femoral neck stress fracture algorithm which may be used to determine treatment. *Hx* history, *PE* physical examination, MRI magnetic resonance imaging, *Fx* fracture, *NWB* non-weight bearing, *FROM* full range of motion

evaluation and treatment of the child with a stress femoral neck fracture (Fig. 5.2) [17]. Although there is some variation regarding treatment for femoral neck stress fractures, it is suggested that non-displaced fractures on the tension side of the femoral neck should undergo internal fixation [18]. Fractures on the compression (medial) aspect of the femoral neck can be initially treated non-operatively with restricted weight bearing or non-weight bearing. The length of time for weight-bearing restriction can vary between 4 and 8 weeks. Weight bearing can be advanced once the patient is asymptomatic and has full range of motion of the affected hip. If there is concern about the patient's ability to maintain the restricted weight-bearing status, then percutaneous internal fixation should be considered.

Classification

Femoral neck fractures were originally classified by Delbet in 1907 and reported by Colonna [19]. The classification is commonly used and has proven to be useful and applicable since it not only allows for an accurate morphological assessment, but it also has prognostic significance (Fig. 5.3). In 2006, Moon et al. [20] demonstrated that the risk for development of osteonecrosis increases with the complexity of the fracture and progressively correlates with the Delbet type of injury. Types I, II, and III fractures were 15, 6, and 4 times more likely to develop ON than type IV fractures, respectively. ON rate by Delbet class was I = 38 %, II = 28 %, III = 18 %, and IV = 5 %; this rate of ON has been corroborated in more recent reports [20].

Type I: Transphyseal Fractures

Overall rare, Type I transepiphyseal fractures (Fig. 5.4) constitute 8 % of femoral neck fractures. An isolated injury through the proximal femoral physis is labeled -IA. Type IB has an associated femoral head dislocation from the acetabulum, and it can be present in up to 50 % of Type I fractures. Type IB fractures usually present in young children involved in high-energy trauma. It has also been reported as iatrogenic physeal fracture during closed reduction of a dislocated hip [21]. It is unclear if injury to the growth plate occurs during trauma or with forceful reduction maneuvers thereafter. For this reason, we recommend that closed reduction of a hip dislocation in a child with open proximal physis should be performed under sedation with fluoroscopic guidance in the operating room. The surgeon should consider percutaneous pin fixation of the physis prior to reduction if fluoroscopic

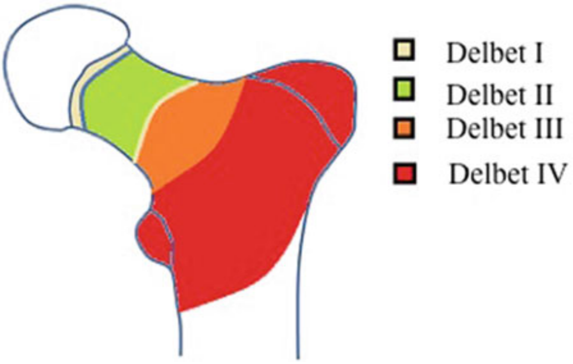

Fig. 5.3 Delbet classification of hip fractures in children. I, transepiphyseal with (IB) or without (IA) dislocation from the acetabulum; II, transcervical; III, cervicotrochanteric; and IV, intertrochanteric

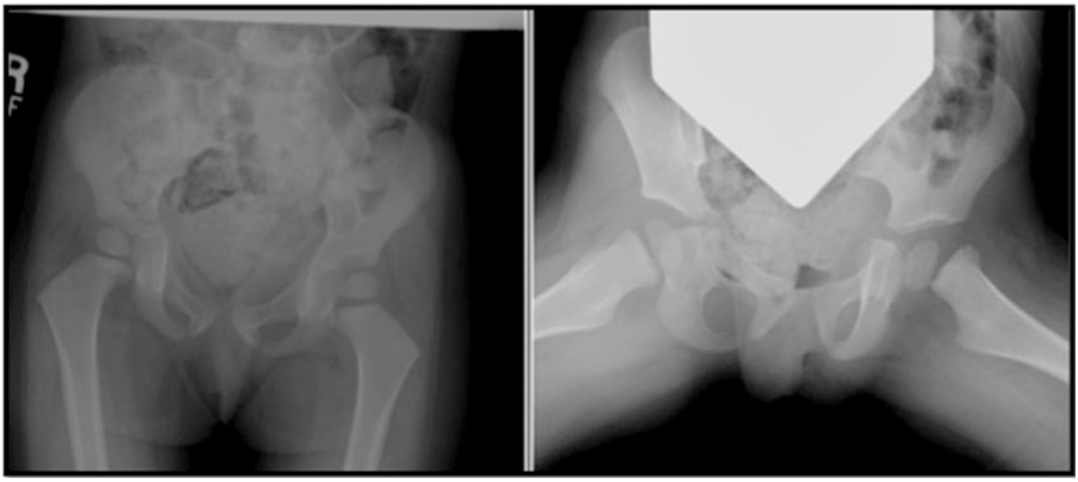

Fig. 5.4 AP pelvis and frog lateral X-ray demonstrating a Delbet Type I fracture in a 25-month-old male

views suggest instability of the physis as evidenced by displacement or abnormal separation of the ossific nucleus from the metaphysis compared to the normal contralateral hip. Injuries with femoral head dislocation have a poor prognosis in children. High rates of ON have been described, and premature physeal closure has been reported to be as high as 100 % [1].

Type II: Transcervical Fractures

Transcervical fractures (Fig. 5.5) are the most common type of hip fracture, accounting for half of proximal femur fractures in children. Fortunately, a non-displaced fracture has a low incidence of ON. However, with displaced Type II fractures, the rate of ON has been reported to be 28 % [20]. ON most commonly develops in older children and different etiologies have been proposed, including vessel kinking, and disruption secondary to displacement, as well as increased intracapsular pressure after the fracture.

Type III: Cervicotrocanteric Fractures

Type III fractures (Fig. 5.6) have similar outcomes to type II fractures. Type III injuries are distal on the neck and have an incidence of ON reported from 18 to 30 % in displaced fractures. Appropriate anatomic reduction and fracture site compression can decrease the incidence of this complication [22].

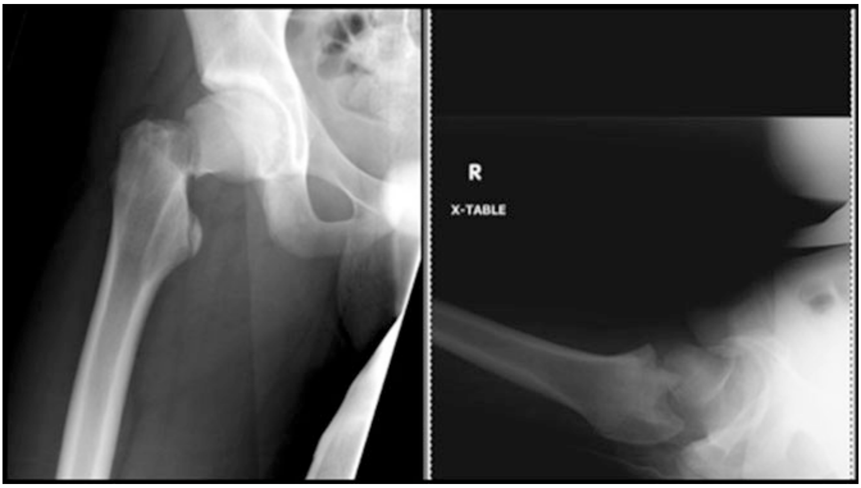

Fig. 5.5 AP and lateral X-ray of a 13-year-old male with Delbet Type II femoral neck fracture

Fig. 5.6 Radiograph of a patient with a Delbet Type III cervicotrochanteric fracture

Type IV: Intertrochanteric Fractures

Type IV fractures (Fig. 5.7) have the lowest complication rates, and generally good outcomes secondary to its extracapsular nature. ON rates are reported to be close to 5 %; reports of physeal closure and coxa vara are rare, but have been published.

Treatment

Non-operative Management

Type I non-displaced physeal neck fractures in patients under 2 years of age can be managed with spica casting and close observation to assure no displacement. In patients with mild displacement, a gentle attempt of closed reduction can be performed. If the reduction is anatomic, then stable casting can be performed without fixation. Spica casting should be done with the limb abducted and in neutral rotation to avoid varus and external rotation displacement. Serial radiographs should be obtained 3–5 days after initial casting and then weekly for 3–4 weeks to confirm maintained alignment and healing. Early fracture displacement should warrant immediate fracture reduction and fixation. Spica cast should be utilized for 6 weeks until the fracture is healed.

Non-displaced Type IV fractures in children under 4 years of age can be treated with 12 weeks of spica casting. Again, close observation should be employed, with a low threshold for operative fixation in the setting of displacement. Weekly radiographs for the initial 3–4 weeks are recommended. If the castradiographs are difficult to interpret and displacement is questionable, a limited hip CT scan should be performed to confirm reduction [1].

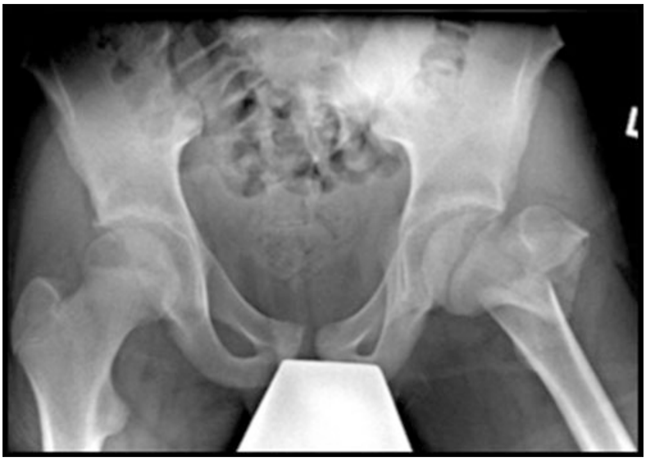

Fig. 5.7 Radiograph of a 13-year-old male with Delbet Type IV fracture

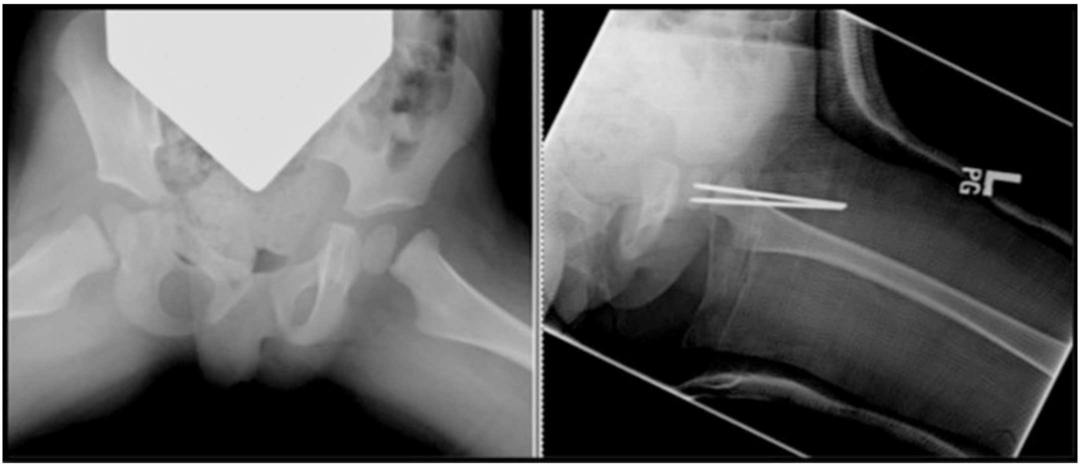

Fig. 5.8 (**a**, **b**) Radiographs of a 25-month-old who sustained an injury during a fall. (**a**) Radiograph showing a preop physeal separation. (**b**) Postoperative radiograph on spica cast after transphyseal K wires

Operative Management

Closed Reduction and Percutaneous Pinning

Closed reduction and pinning can be performed for certain anatomically reducible neck fractures and in certain physeal separations.

In very young infants and toddlers (under age 2) with unstable physeal separations (Type I) or unstable neck fractures Types II and III, smooth 2 mm Kirschner wires can provide sufficient fixation (Fig. 5.8a, b). For older children above ages 4–6 years with displaced unstable fractures including Type I physeal separations, II and III fractures, cannulated screw fixation is necessary [1]. Respect for fracture stability is of utmost importance, and crossing the physis to obtain stability is more important than potentially creating a minor leg length discrepancy from a premature physeal arrest. Inadequate fixation of the proximal fragment because of fixation short of the physes often results in late displacement and a high rate of ON. In children up to age 8 years, 4.0–4.5 mm cannulated screws can be used; in older children, 6.5 mm cannulated systems are indicated.

Technique

The patient is positioned supine on a flat radiolucent table; a fracture table can also be used depending on the surgeon's preference and institution's availability. C-arm fluoroscopy is brought in from the contralateral side; AP and lateral frog views should be obtained prior to starting the procedure to confirm appropriate visualization, without moving the leg to obtain these images.

If fluoroscopy imaging demonstrates fracture displacement, traction internal rotation and abduction are usually necessary to obtain anatomic alignment. If reduction is not anatomic, the surgeon should change plans and perform an open reduction. The greater trochanter (GT) is marked on the skin laterally and percutaneous fixation is inserted laterally through the tensor fasciae latae (TFL) just below the GT but not distal to the lesser trochanter, to prevent the creation of a "stress riser." K wires or guide wires for cannulated screws are passed through the femoral neck under direct fluoroscopic visualization.

Two or three wires provide enough stability. Wires should be placed across the physis in a parallel fashion. Once appropriate X-ray confirmation of reduction and pin placement is confirmed, wires should be cut and bent over the lateral femoral cortex under the skin. This requires a second procedure for removal of hardware, but avoids migration or risk of infection. In older children, over age 3, reaming can be performed over the pins and appropriate-length cannulated screws placed. Screws should be placed across the physeal scar to prevent torsion stress transfer to the physis. AP and lateral views should confirm adequate screw/pin placement; a total of two screws are sufficient in young children and in older adolescents, three screws give excellent fixation but sometimes are difficult to insert due to the size. Screws should be drilled and tapped to avoid rotational fracture displacement during screw insertion. Some authors recommend hip joint aspiration to relieve the hemarthrosis that can theoretically decrease flow of the retinacular vessels to the femoral head [23].

Open Reduction

Open reduction of a femoral neck fracture is indicated when anatomic closed reduction cannot be attained by gentle manipulation. The fractures that require this type of procedure should be treated in an urgent manner (<24 h) since this potentially decreases the risk of developing ON [23].

Approaches

An anterolateral (Watson-Jones) is a useful approach for Delbet Types Ia, II, and III femoral neck fractures. The patient is positioned supine with the greater trochanter on the edge of a flat radiolucent table.

A 5–8 cm straight longitudinal incision is centered on the tip of the greater trochanter. With this approach there is no true internervous plane; gluteus medius and the tensor fasciae latae (TFL) are both innervated by the superior gluteal nerve.

The interval between TFL and gluteus medius is developed bluntly and retractors placed to expose gluteus medius and vastus lateralis distally. The anterior border of gluteus medius is identified and retracted posterior/superiorly or, if necessary, a third of its insertion is elevated from the GT. This will expose the femoral neck and the hip capsule and allow for open reduction of a femoral neck fracture and or decompression of the hip joint [24].

A lateral (Hardinge) approach is useful for Delbet Type Ib and IV femoral neck fractures. The patient is positioned supine with greater trochanter on edge of flat radiolucent table. The incision is 5–8 cm straight longitudinal centered on the tip of the greater trochanter.

There is no true internervous plane; gluteus medius and the tensor fasciae latae (TFL) are innervated by the superior gluteal nerve. The dissection is between the interval between TFL and gluteus medius, is developed bluntly, and retractors placed to expose gluteus medius and vastus lateralis distally. The gluteus medius is identified and split, starting in the midpoint of the insertion on the GT and continuing proximally for a maximum of 3 cm. Injury to SGN can be caused if dissection is carried further proximally.

The anterior part of the gluteus medius muscle with its underlying gluteus minimus and the anterior part of the vastus lateralis muscle are elevated from the GT and retracted anteriorly. After this is

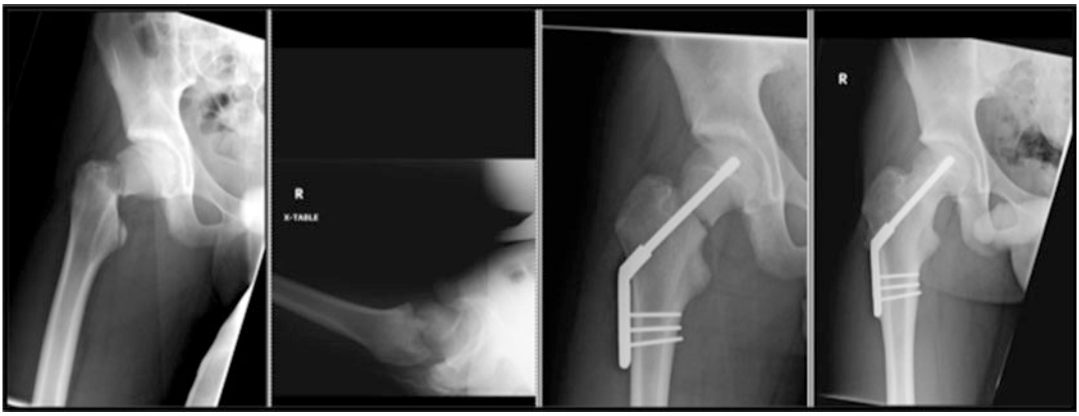

Fig. 5.9 Radiographs of a 13-year-old male who underwent fixation with a dynamic hip screw for a femoral neck fracture

done, the femoral neck and the anterior hip joint capsule will be exposed [24].

Once adequate exposure of the fracture site is achieved, anatomic reduction of the fragments is performed with the help of bone-reduction clamps. The femoral neck can be brought anteriorly with the help of a bone hook placed anteriorly over the medial neck, and after reduction is achieved, this is confirmed with fluoroscopy and palpation. Fixation with cannulated screws or pins is performed as described above.

Occasionally, it is useful to perform an anterior Smith-Peteresen approach combined with a lateral approach. This allows optimal visualization of the fracture and assurance of a decompression with anatomic reduction, as the anterior approach will bring the exposure directly down onto the fracture site. This approach should be familiar to most orthopedic surgeons and utilizes the interval between the tensor and sartorius superficially, and exposing and retracting the rectus at the deep layer. This exposes the capsule which can be opened directly on the neck. The concomitant lateral approach will allow for further control of the fracture and for optimal exposure for implant placement.

Plate Fixation

There are a variety of implants available for fractures amenable to plate fixation, which are usually Delbet Type III and IV fractures. The available implants include standard dynamic hip screw constructs, which are sized for children, adolescents, and adults (Fig. 5.9). There are also newer generation pediatric locking plates which allow for locking screw placement into the femoral neck. These come in sizes of small (3.5 mm) or larger (5.00 mm) and have varying degrees of fixed screw-plate angles. There are no surgeon-specific guidelines for which size implant to use, and having a couple of sizes available will allow for intraoperative decision given the size of the femur.

A pediatric plate and screw device provides excellent fixation for Type III and IV fractures, as failures of cannulated screws can occur (Fig. 5.10a–c).

Technique

Incision is made starting at the base of the GT and carried on distally. Usually 6–8 cm is sufficient for plate fixation. Subcutaneous tissue is divided with the use of eletrocautery and TFL is exposed and incised in line with its fibers. The vastus lateralis is then visualized and an "L" type incision over its fascia is performed, detaching it vertically 1 cm distal from its insertion on the GT, and then in line with its fibers longitudinally on the posterior border. Leaving a 5 mm posterior cuff of vastus fascia can aid in later closure.

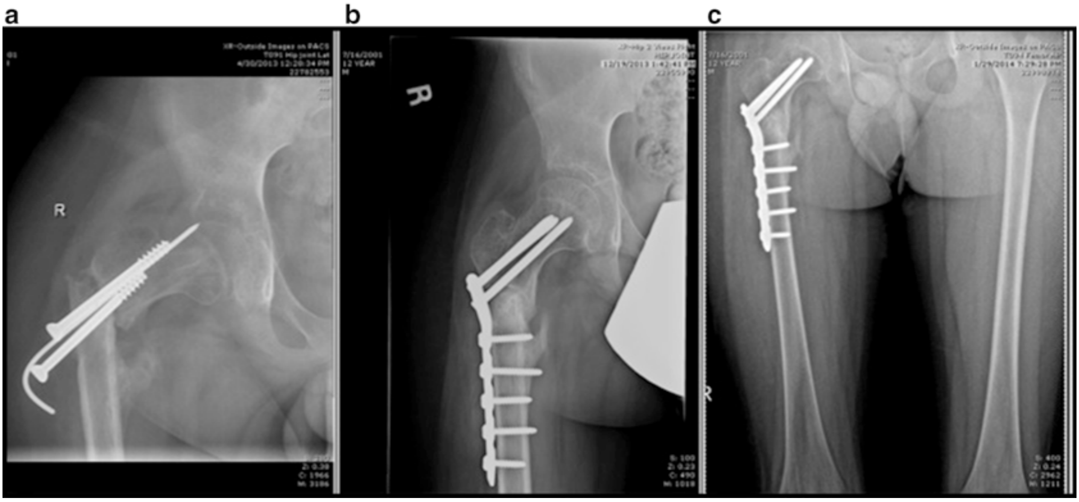

Fig. 5.10 (**a**–**c**) 12-year-old male with intertrochanteric fracture. (**a**) Nonunion after cannulated screw fixation. (**b**) Revision nonunion with valgus realignment and proximal femoral 5.00 mm locking plate. (**c**) 6-week follow-up with interval healing

The sub-vastus approach is carried out elevating vastus anteriorly and exposing the lateral femoral cortex.

Once reduction is confirmed, a guide wire is drilled through the center of the femoral neck. This can be drilled with a device guide, achieving the appropriate femoral neck-shaft angle (most commonly a 135° device is utilized). The guide wire does not need to transfix the femoral physis for Type IV fractures; position is confirmed with AP and lateral fluoroscopic views. Before drilling, an anti-torque wire can be placed parallel and superior to the hip screw guidewire to avoid rotational displacement. The appropriate screw length is measured with a depth gauge and the screw hole is drilled over the guide wire. The lag screw is placed and a three-hole side plate is passed over the screw. The plate is secured with bicortical screws and final hardware positioning is checked under fluoroscopy.

Newer generation locking-plate fixation is performed in a similar manner with cannulated techniques, to allow for optimal locking screw placement via placement of correctly placed guide wires through plate-specific guides. These plate–screw constructs allow potentially greater fixation in osteopenic bone than a dynamic hip screw, giving the locking technology and the ability to place multiple screws into the femoral neck.

Postoperative Management

A spica cast should be used in patients who have risk of displacement after operative management, because of limited fixation (k-wires), uncontrollable behavior, or poor bone biology. In general, most children under age 8 will tolerate a one-legged spica appropriately. The spica can be maintained for 6 weeks in patients under 8 years of age with Delbet I, II, and III fractures. For patients requiring spica cast immobilization after a closed reduction, weekly radiographic follow-up should be maintained for 3–4 weeks until callus formation is present. Older patients as well as Delbet Type IV fractures should receive stable fixation, and they will likely be stable enough to allow for progressive weight bearing.

A gradual return to weight-bearing activities is instituted after evidence of callus formation and fracture healing, usually at a minimum of 6 weeks. However, most families should be counseled regarding non-weight bearing for up to 3 months. Return to regular activities can be allowed at 3–6 months after injury if clinical and radiographic healing is evident and appropriate rehab has been performed. Return to full sports can be allowed after return of painless range of motion and full strength. Follow-up should be done on a regular basis approximately every third month for the first year to monitor for ON, and then yearly until maturity in order to evaluate for femoral neck fracture complications.

Complications and Outcomes

Due to the fact that femoral neck fractures have high rates of complications, operative management has increased in the last few decades. It is well known that anatomic reduction will improve outcomes and avoid malunions. Outcomes after femoral neck fractures have been studied, and recent reports have demonstrated good outcomes in approximately 60 %, fair in 20 %, and poor results in 20 % of patients with this injury [23].

Osteonecrosis (ON)

Osteonecrosis is the most severe complication following femoral neck fractures in the pediatric population, and also the most difficult to manage. Greater rates of ON and nonunion are seen with higher energy fractures such as Delbet I and II fractures. Recent reviews have reported a 23 % average of ON after femoral neck fractures ranging from 40 % in Delbet I (a rate of 100 % was for IB fx) to 5 % in Type IV fractures. Rates of ON in fractures treated with open reduction are 2.5 times higher than with closed reduction, but it is unclear if this is due to the surgical treatment or more likely to the severity of the injury requiring an open reduction. Urgency of surgical reduction is also relevant when treating femoral neck fractures, as the risk of ON is four times higher when definitive treatment is delayed greater than 24 h after injury. Decompression of the hip joint after a femoral neck fracture remains controversial. Some studies have supported joint decompression, but others have failed to find differences in risk of ON [23–27]. The authors believe that when an open reduction is required, a routine decompression can be performed with low morbidity, and hence recommend decompressing the joint in displaced femoral neck fractures. Review of 72 femoral neck fractures at the authors' institution has demonstrated that displacement, treatment within 24 h, and fracture type are significant predictors of a patient developing ON. Odds of developing ON after suffering a displaced femoral neck fracture are 9.4 times the odds of a subject without a displaced fracture (95 % CI 1.3–69.5). Delbet Type I had 14 times the odds of developing ON (95 % CI: 1.08–175.58) and Type II fractures had four times the odds of developing ON (95 % CI: 1.09–16.41) when compared to Type III fractures [28].

The treatment of femoral head ON should take into consideration the patient factors such as age, activity level, and medical comorbidities, along with the clinical and radiological findings. The size and location of the necrotic segment, degree of femoral head depression, presence of acetabular involvement, and the morbidity of the surgical procedure planned are the major factors in deciding the treatment plan.

Treatment options for ON can be categorized as: non-surgical/medical treatment, joint-preserving procedures, and prosthetic replacements. The role of medications in osteonecrosis is still experimental and limited. Proposed medications include low-molecular-weight heparins, statins, and bisphosphonates. Many joint-preserving procedures have been described for the management of precollapse and early stages of ON. There is no single procedure that has produced reproducible and satisfactory long-term results. Some of the commonly used joint-preserving surgical procedures include:

- Core decompression
- Vascularized bone grafting
- Non-vascularized bone grafting
- Bone marrow and bone morphogenic protein injection
- Acetabular and femoral osteotomies

Nonunion

Femoral neck nonunion is defined as a failure of fracture healing greater than 6 months after initial treatment, and is a complication which occurs in approximately 11 % of pediatric femoral neck fractures. Delbet Type II fractures have an increased risk of nonunion, while Type IV present a smaller risk, which is related to the anatomical blood supply. Mechanical forces related to non-stable fixation can be implicated in the majority of cases. The presentation of a nonunion requires further operative treatment to decrease the shear forces at the fracture site; commonly this is facilitated with a subtrochanteric valgus femoral osteotomy.

Infection

Infection is a rare complication following pediatric femoral neck fracture fixation. Irrigation and debridement should be performed; implant retention is usually necessary until fracture healing has occurred. Appropriate cultures should be obtained and intravenous antibiotics should be used according to the results of the cultures. Femoral neck infection can progress into a nonunion, malunion, or osteonecrosis, thus further complicating the patient's outcome, as such early aggressive treatment can minimize these potential complications.

Malunion/Coxa Vara and Premature Physeal Closure (PPC)

Coxa vara is defined as a femoral neck-shaft angle of <120° and is the second most common complication of hip fractures in children. In a recent meta-analysis, coxa vara was reported to be present in 153 of 828 patients (18.5 %) with femoral neck fractures. Review of the literature demonstrates that the risk of coxa vara is decreased in patients treated operatively, and is a clear risk factor for development of hip osteoarthritis (OA). Epyphysiodesis of the greater trochanter is a treatment option for children younger than age 8 years to prevent further variation. PPC has been reported to develop in 22 % of patients with this injury [23]. Closure of the physis will affect patients differently depending on the age of presentation. Secondary angular deformity and leg length discrepancy on occasions will require further surgical treatment.

Conclusions

- Femoral neck fractures are rare in the pediatric population, but the potential complications are severe, and pediatric orthopedic surgeons must be familiar with management of each type of injury appropriately in order to minimize risk of developing complications.
- The Delbet classification is reliable and prognostic, and currently the preferred classification for femoral neck fractures.
- Anatomic reduction can decrease deformity and should be the goal of operative intervention. Displaced femoral neck fractures should be treated urgently (<24 h) to decrease risk of ON.
- Patients under age 8 with risk of displacement after operative management should be considered for immobilization with a one-legged spica.
- Incidences for ON, nonunion, coxa vara, and PPC are 23 %, 8 %, 17 %, and 22 %, respectively. Incidence of complications rises according to severity of injury.
- Displacement, treatment within 24 h, and fracture type are significant predictors of a patient developing ON.

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Subtrochanteric Femur Fractures in Children

6

Mark Seeley, Michelle S. Caird, and Ying Li

Introduction

Fractures in the subtrochanteric region are a particularly challenging subset of femur fractures to manage. These fractures are rare and account for 4–17 % of pediatric femur fractures [1–3]. The mechanism of injury, treatment, and associated complications are significantly different from femoral shaft and intertrochanteric femur fractures, owing to the strong muscle forces, bending moments, and complex fracture patterns that can occur with subtrochanteric femur fractures. Obtaining and maintaining fracture reduction is challenging secondary to flexion, abduction, and external rotation of the proximal fragment, relative to the distal fragment. Treatment selection is based on patient age, weight, femoral canal size, fracture stability, associated injuries, and surgeon experience. Few studies have evaluated the outcomes and complications of treatment of subtrochanteric femur fractures in children.

Classification

There is no consensus in the literature on the definition of a pediatric subtrochanteric femur fracture. Several definitions exist, including any fracture that is located in the proximal quarter of the femoral shaft or within 3 cm of the lesser trochanter [2, 4]. However, some subtrochanteric femur fractures do not fit perfectly into this classification, with fracture lines extending proximal to the lesser trochanter or distally into the diaphysis. Pombo and Shilt identified a pediatric subtrochanteric femur fracture as a fracture that is located within the proximal 10 % of the total femur length below the lesser trochanter (Fig. 6.1). This formula is a modification of one adult definition of a subtrochanteric femur fracture, which includes any fracture that occurs within 5 cm of the lesser trochanter, based on the average length of the adult femur [5]. Pombo and Shilt's modification is the authors' preferred definition, as it takes into account the difference in femur lengths at various ages, as well as the difference in femur lengths among children of the same age.

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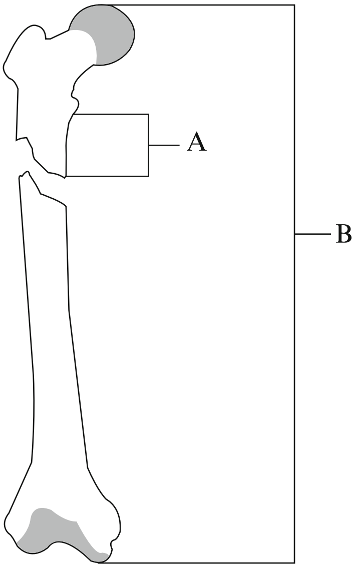

Fig. 6.1 The authors prefer this method to classify subtrochanteric femur fractures. A full-length anteroposterior femur radiograph is used to determine the total length of the femur (*B*), which is defined as the distance between the top of the femoral head and the medial femoral condyle. Next, the distance between the inferior aspect of the lesser trochanter and the fracture site is measured (*A*). If $(A/B) \times 100 = 10\,\%$ or less of the total length of the femur, the fracture is classified as subtrochanteric

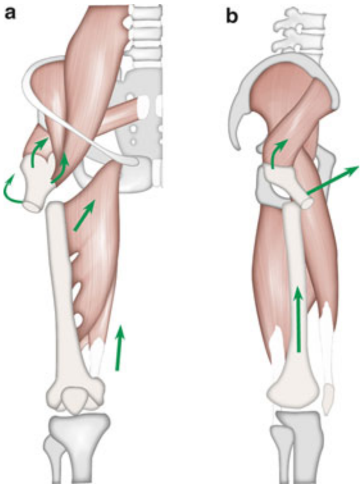

Fig. 6.2 (**a**) AP and (**b**) lateral diagrams of the muscle forces in a subtrochanteric femur fracture. The subtrochanteric region of the femoral shaft is almost completely encased in a muscular envelope. The quadriceps and hamstrings span the proximal femur, and contribute to femoral shortening. The integrity of the trochanters influences fracture deformity. If the majority of the fracture is below the lesser trochanter, the proximal segment typically externally rotates, flexes, and abducts due to the muscular pull of the short external rotators, iliopsoas, and hip abductors. The hip adductors medialize the distal shaft of the femur. In contrast, if the lesser trochanter is involved in the fracture, this results in decreased flexion and external rotation deformities of the proximal fragment produced by the psoas muscle

Anatomy

Knowledge of the proximal femoral anatomy is crucial in order to understand the deforming forces that must be overcome to achieve anatomic alignment. The subtrochanteric region of the femoral shaft is almost completely encased in a muscular envelope. The quadriceps and hamstrings span the proximal femur, and contribute to the femoral shortening that occurs after a subtrochanteric femur fracture (Fig. 6.2). The integrity of the trochanters influences fracture deformity. If the majority of the fracture is below the lesser trochanter, the proximal segment typically externally rotates, flexes, and abducts due to the muscular pull of the short external rotators, iliopsoas, and hip abductors, respectively. The hip adductors, in turn, generally medialize the distal shaft of the femur, as shown in Fig. 6.2. In contrast, if the lesser trochanter is involved in the distal fracture fragment, this results in decreased flexion and external rotation deformities of the proximal fragment produced by the psoas muscle. Understanding the pathophysiology of the fracture is crucial to obtain proper reduction, since longitudinal traction alone is unlikely to correct the deformity. The treating surgeon should anticipate the need to utilize several reduction techniques, either through positioning or externally applied forces, to control the fracture segments and obtain proper alignment.

Biomechanics

The majority of the studies evaluating the biomechanics of the subtrochanteric region have been conducted in adult cadaveric and computer models. Although there are many similarities in the stresses seen in the subtrochanteric region, the results of these studies cannot be fully applied to a pediatric model because the primarily cartilaginous skeleton can better distribute stresses. During ambulation, the femur is subjected to high compressive, tensile, and torsional forces as a result of body weight and the multiple deforming muscle forces exerted on the proximal femur. The majority of these forces are concentrated in the subtrochanteric region [6]. In 1917, Koch et al. created a mathematical beam model of a femur, which was represented as a curved beam with a 100-pound force applied at the femoral head. The authors found that the highest stresses in compression occurred just at the base of the medial subtrochanteric region, and in tension, just below the greater trochanter. This work has been further elaborated on and substantiated by several researchers using various methods, ranging from finite element analysis to 3-D CT modeling [7, 8]. In general, the fracture pattern is determined by the magnitude of the applied load, the rate of load application, and the local strength of the femur.

Mechanism of Injury

The incidence of femur fractures has increased in recent decades, which likely correlates with greater participation in organized sports and physical extracurricular activities [9]. The osseous failure in subtrochanteric fractures may be due to pure torsion, or a combination of torsion and bending. These fractures are found across all age groups and are attributable to a number of mechanisms. High-energy trauma is the most common mechanism, such as motor vehicle accidents or falls. There is an asymmetric age- and gender-related distribution of subtrochanteric femur fractures, with these injuries occurring more frequently in younger children [2, 4, 10] and males [2, 4, 11].

Evaluation

History

A complete history is vital to the proper management of a patient with a subtrochanteric femur fracture. This can be obtained from the patient, family members, and emergency medical personnel. The pertinent pieces of information that must be documented are the patient's age, mechanism of injury, need for extrication, and any comorbid conditions. Nonaccidental trauma should always be considered in a nonambulatory child. Although fractures associated with nonaccidental trauma are more common in the distal femur, the evaluating physician should assess for signs suggestive of child abuse, such as bruises, burns, late presentation, or fractures in various stages of healing [12]. If the subtrochanteric femur fracture resulted from a low-energy mechanism, evaluation for a pathologic bone condition should be conducted.

Physical Examination

The patient with a subtrochanteric femur fracture usually presents with a lower extremity that is shortened, flexed, and externally rotated secondary to the deforming muscles forces. The extremity should be inspected for any skin disruption, which may indicate an open fracture. The circumference of the hip and thigh should be evaluated and monitored for potential compartment syndrome or an expanding deep hematoma. The knee should be assessed for ligamentous injury and a thorough vascular examination should be performed, including the popliteal, dorsalis pedis, and posterior tibial pulses. The sciatic nerve is in close proximity to the subtrochanteric region, and documentation of the motor and sensory function of the tibial and peroneal nerves is required. The contralateral lower extremity can be assessed to evaluate relative leg lengths. It is imperative to perform a detailed evaluation for other sites of discomfort that may be masked by pain from the femur fracture. A methodical examination of all extremities and the pelvis should be performed to assess for associated fractures. Associated injuries are common in young patients with a high-energy mechanism of injury. Ipsilateral noncontiguous pelvic injuries and other ipsilateral fractures can occur.

It is uncommon for patients with isolated femoral fractures to have hemodynamic insufficiency, and aggressive volume support is usually not needed. Further investigation into associated abdominal, thoracic, or cranial etiology is warranted in patients who are hypotensive, hypovolemic, or anemic. A study assessing 149 children who sustained a femur fracture secondary to a motor vehicle accident found that 18.5 % of patients had an associated soft-tissue injury, 5 % had an intra-abdominal injury, and 14 % had a head injury [13].

Radiographic Studies

Radiographic evaluation should begin with an anteroposterior (AP) pelvis radiograph, and full-length AP and lateral radiographs of the entire femur. Traction radiographs may be helpful to delineate subtle fracture lines, although these may be difficult to obtain in the acute injury setting. Fracture pattern, comminution, bone loss, and associated fractures should be assessed. Signs of an underlying pathologic bony process should be noted, such as osteopenia or a radiolucent lesion. If nonaccidental trauma is suspected, a skeletal survey should be obtained to evaluate for additional fractures. This should consist of AP radiographs of the long bones of all four extremities, AP and lateral views of the thoracolumbar spine, and an AP and lateral skull series. A single radiograph of the entire child is not sufficient, as this is likely to miss fractures [14].

Computed tomography (CT) is not usually necessary in the routine evaluation of subtrochanteric femur fractures. Magnetic resonance imaging may be indicated if a pathologic fracture or stress fracture is suspected. If there is concern for vascular compromise, ankle-brachial indices are a quick subjective measurement of limb perfusion that can be obtained in the trauma bay.

Management Principles

The timing of definitive fixation is dictated by the patient's hemodynamic stability and associated injuries. Although the treatment of subtrochanteric femur fractures has been predominantly age-based (Table 6.1), the treating surgeon must take into account the patient's body habitus and skeletal age. Treatment failures occur when there is a mismatch between the biomechanical demands of the fracture and construct stability. In general, overriding of the fracture segments by 2 cm or more indicates disruption of the periosteal sleeve and can be used as an indicator of fracture stability. The ideal device for stabilization of subtrochanteric fractures is an implant that resists the tendency for shaft medialization, as well as external rotation, flexion, and varus angulation of the proximal fragment [15].

Fracture malalignment is a commonly reported complication from subtrochanteric femur fractures [16–21]. The majority of the criteria used for acceptable shortening and angulation at the fracture site originate from the femoral shaft literature. Caution should be used when applying these principles to the assessment of subtrochanteric femur fractures because functional outcome studies assessing proximal femur angular deformities are lacking. In general, fracture shortening is tolerated in children younger than 10 years of age because of the physiologic growth stimulation that occurs during fracture healing and subsequent

Table 6.1 Recommended treatment options for pediatric subtrochanteric femur fractures

Age	Pavlik harness	Spica cast	External fixation	Flexible intramedullary nailing	Open plating	Submuscular plating	Rigid intramedullary nailing
≤6 months	+++	++	–	–	–	–	–
6 months to 5 years	–	+++	+	++	++	++	–
5–11 years	–	–	+	++	++	+++	–
≥11 years	–	–	–	–	++	++	+++

+ authors' least preferred option, ++ authors' accepted option, +++ authors' preferred option femoral overgrowth following such fractures [2, 4, 22–24]. Therefore, 1.0–1.5 cm of shortening is considered acceptable in this young age group.

Due to the remodeling potential of the femur, coronal and sagittal malalignment can be tolerated up to 20–25° before abductor function becomes compromised [2, 4, 22, 25–27]. Jeng et al. followed 15 children treated with 90–90 traction for a subtrochanteric femur fracture for approximately 6.5 years. Remodeling of coronal angulation was 50 % or more in all cases. However, the average age of patients in the study was 4.5 years, making it difficult to extrapolate the results to adolescents who have decreased growth and remodeling potential [2].

Unlike coronal or sagittal angular deformities, torsional deformities have been found to have less remodeling potential but are generally well compensated by patients [28]. The treating surgeon should carefully scrutinize preoperative and intraoperative imaging, which may include the relationship of the lesser and greater trochanters of the contralateral side, or that of one or both of the trochanters to the distal femoral condyles, to accurately assess the rotational deformity and attempt to correct this during treatment.

Nonoperative Management

Pavlik Harness

The Pavlik harness is the preferred treatment for femoral shaft fractures in children 6 months of age and younger. Notably, however, there are no published reports of pediatric subtrochanteric femur fractures treated with a Pavlik harness. The thick periosteum in this age group results in relative fracture stability. Several authors have reported excellent functional outcomes after Pavlik harness treatment of femoral shaft fractures due to the robust fracture remodeling potential in the infant and toddler [29, 30]. Podeszwa et al. assessed the radiographic and functional results of 40 children under 1 year who had sustained a femur fracture; 24 patients were treated with a Pavlik harness, while 16 patients were treated in a spica cast. They found no difference in radiographic outcomes between the two groups. Approximately one-third of the spica cast patients had a skin complication, which was not seen in the Pavlik harness group [29, 31]. Although a similar study has not been performed in subtrochanteric fractures, we recommend a Pavlik harness for children 0–6 months of age (Table 6.2).

Table 6.2 Technical tips for Pavlik harness treatment

Anesthesia:	None
Position:	Supine
Steps:	• Traction is applied to the affected limb while an assistant places the shoulder straps, chest band, and the normal limb in the stirrup.
	• The hip of the affected limb is flexed approximately 80° and is abducted no more than 50°.
	• Pillow or blankets can be used to help prevent the affected leg from falling into abduction when at rest.
Postoperative care:	• Weekly follow-up until the fracture is healed.
	• AP and lateral radiographs are obtained at each visit.
	• Adjustments are made to Pavlik harness based on radiographs.
	• Duration of treatment is usually 3–4 weeks in the young infant.

Hip Spica Cast

There is a paucity of data regarding the use of spica casting in the treatment of pediatric subtrochanteric femur fractures. Similar to femoral shaft fractures, children 6 months to 5 years of age can be considered for spica cast treatment. However, because unstable femoral shaft fractures have been shown to displace with spica cast treatment [31, 32], determination of fracture stability is equally, if not more, important when determining the optimal treatment for subtrochanteric femur fractures. The majority of subtrochanteric fractures are difficult to manage with closed means, secondary to the strong deforming muscle forces and high-energy mechanism of injury. Jarvis et al. evaluated 13 skeletally immature adolescents who had undergone treatment of a subtrochanteric femur fracture. Ten patients were treated operatively with a variety of different techniques, while three patients were

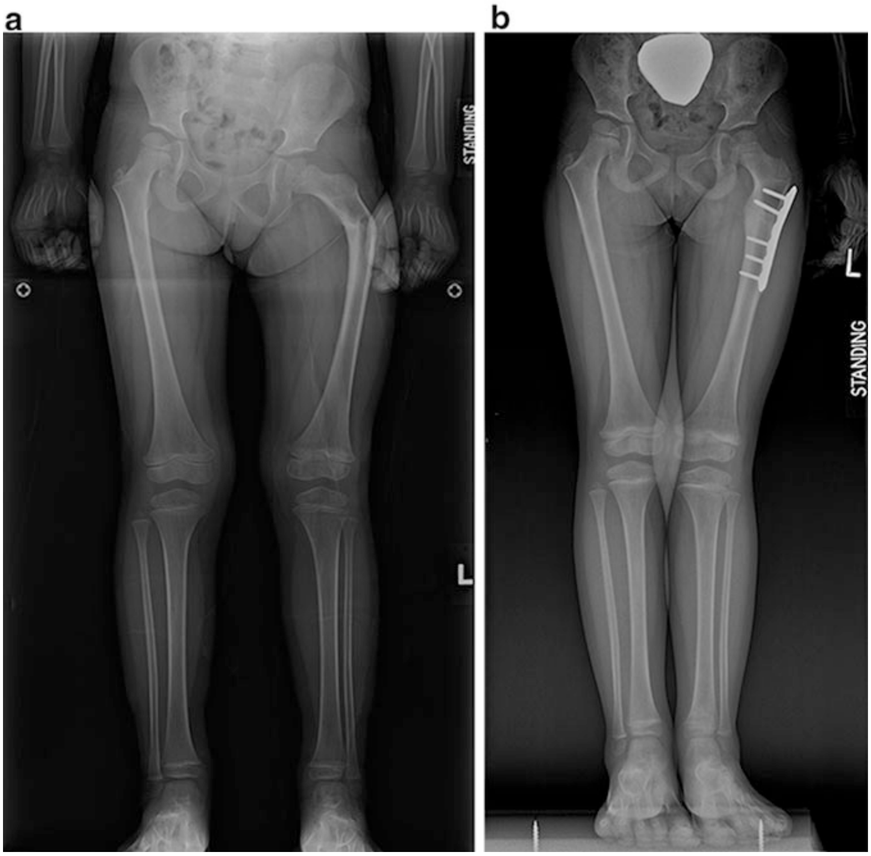

Fig. 6.3 (**a**) Standing AP lower extremity radiographi of a 3-year-old female who sustained a subtrochanteric femur fracture after jumping from a bed. The patient was treated in a spica cast for 8 weeks at an outside facility and was seen as a second opinion for a leg length discrepancy 6 months later. (**b**) Patient 15 months following a subtrochanteric osteotomy

treated nonoperatively with a spica cast. At final follow-up, all of the patients who were treated nonoperatively had unsatisfactory outcomes, with fracture malalignment ranging from 8 to 16° and subsequent leg length inequalities. The authors concluded that internal fixation was more effective than nonoperative treatment of subtrochanteric femur fractures in skeletally immature adolescents [33]. Although children younger than 5 years have increased remodeling potential compared with adolescents, and are more likely to have a good outcome when managed in a spica cast, we advise careful assessment of fracture stability when deciding between spica cast versus operative management of a subtrochanteric femur fracture in this age group. Close radiographic and clinical follow-up is necessary if cast treatment is undertaken (Fig. 6.3a, b), as skin-related complications are also common with spica casting (Table 6.3).

Operative Management

External Fixation

External fixation for treatment of subtrochanteric fractures is generally reserved for open fractures, fractures with associated neurovascular injury, and polytrauma patients [34]. One advantage of external fixation is the ability to perform serial adjustments if the reduction is inadequate. In uniplanar constructs, lateral half-pin frames allow for control of the fracture, as well as mobilization of adjacent joints. Multiplanar external fixators

Table 6.3 Technical tips for spica cast application

Anesthesia:	General with muscle relaxation.
Position:	Supine on a spica table.
Steps:	• Long leg cast is applied first and after it sets incorporate into the torso cast.
	• Applying the long leg cast first allows the surgeon to pull traction through affected extremity with minimal formation of pressure points in the casting material.
	• Important to maintain the knee in 45–60° of flexion and the hip in 45° of flexion during cast application.
	• The foot can be included in the cast in neutral position or left out.
	• Fiberglass is the material of choice. It is soaked in room-temperature water and then rolled using the stretch–relax technique [55] to avoid excessive skin pressure.
	• Assistants should be advised to use the flats of their hands to support the limb during cast application. This prevents indentations in the cast that may cause pressure points and subsequent sores.
	• Cast molding should be performed under fluoroscopy to ensure that proper alignment is maintained.
Postoperative care:	• In general, a good rule of thumb for cast trimming is to leave enough room posteriorly that a caudal block can be given.
	• The perineal area must be trimmed so that adequate room exists for double diapering.
	• Length of time for cast treatment can be determined by patient age in years plus 2 weeks, for a maximum of 12 weeks. • Close follow-up is necessary. The patient is seen every 2–3 weeks until completion of cast treatment.
	• Need to monitor for shortening and varus at fracture site.
	• Need to carefully monitor for skin problems and adequate room for growth.
Other:	• A waterproof cast liner instead of stockinette can decrease skin breakdown.
	• Hip spica casts can be augmented with a connecting bar. This may be beneficial in preventing mechanical failure of the cast.
	• Windows can be cut in the abdominal area for decompression or examination purposes.

allow the adjustment to occur in three planes. With the advent of flexible nails, external fixation is now more commonly used as an initial temporizing measure, rather than for definitive fixation. Although external fixation allows for potential adjustment of fracture position after original operation, better functional outcomes have been demonstrated with femoral shaft fractures treated with flexible nails, with decreased time to full-weight bearing, return to full range of motion, and return to school [34, 35]. No studies have specifically compared external fixation and flexible nailing of pediatric subtrochanteric femur fractures. Refracture after frame removal and pin tract infections are potential complications of external fixation. Wani et al. treated 45 displaced femur fractures in children with external fixation and reported pin tract infections in 47 % (Table 6.4) [36].

Flexible Intramedullary Nailing

Flexible intramedullary nailing is currently the most widely used technique for treatment of femoral shaft fractures in children 5–11 years of age, and remains highly applicable to subtrochanteric fractures as well. This is a minimally invasive, simple, economical, and safe technique. Titanium elastic nailing has demonstrated the best outcomes in patients with length-stable femur fractures in the middle 60 % of the diaphysis who weigh less than 49 kg [16–20, 37–39]. There are only a few reports in the literature on the treatment of pediatric subtrochanteric femur fractures with flexible intramedullary nailing [16–19, 21, 38, 39]. Pombo and Shilt examined 13 patients with an average age of 8.7 years, with subtrochanteric femur fractures treated with titanium elastic nails [5]. They classified their results according to the Titanium Elastic Nails Outcome

Table 6.4 Technical tips for external fixation

Anesthesia:	General with muscle relaxation.
Position:	Supine on a radiolucent table.
Implant selection:	• Steinmann pins can be either a 5-mm standard adult half-pin or a 4-mm half -pin for smaller children.
	• Carbon fiber rods are preferred for their radiolucency.
	• Two bars are appropriate for length-unstable fracture patterns.
	• Two pin–bar clamps are placed on each bar.
Steps:	• Fluoroscopy directs safe and strategic half-pin insertion, as well as manipulative reduction.
	• The initial far distal lateral half-pin is placed first in the distal fracture fragment.
	• The pin is placed through a 1-cm stab wound with the use of a sleeve system.
	• A pin-to-pin connector can then be placed on the initial distal pin. This will allow the surgeon to see where the second distal half-pin needs to be inserted in the lateral aspect of the femur.
	• Next, two half-pins are placed in the proximal fragment, generally around the greater trochanter, in a similar fashion.
	• The length of connecting bar is then selected.
	• Manual traction is applied.
	• The reduction is perfected and the two end pin clamps are tightened to the connecting bars.
	• The bar is positioned in line with the femoral shaft laterally and at least two finger breadths from the skin to allow for any thigh swelling.
	• A short intermediate connecting bar can be added if one of the half-pins was placed at an angle. This configuration also allows for easier adjustment of the fracture reduction after the frame has been applied.
Postoperative care:	• Pin site care is instituted the day after surgery.
	• Sterile, saline-moistened, cotton-tipped applicators are used to for pin site care two to three times daily.
	• Toe-touch weight-bearing is advised for 6 weeks after surgery. The patient is restricted to isometric strengthening exercises for 6 weeks.
	• Weight-bearing is advanced when radiographic healing is evident.
	• When fracture callus is present spanning all four cortices on biplanar radiographs, the external fixation device and pins can be removed.
Other:	• The soft tissues adjacent to the pins may need to be incised to allow unrestricted hip and knee range of motion.
	• Entrapped Steinmann pins in the IT band can decrease knee range of motion.
	• The surgeon should passively range the hip and knee in the operating room, and ensure that the skin and deep tissues are adequately released.

Scoring system [16]. There were no poor results. The only complications were leg length inequalities of 1.6 cm or less in two patients, which were attributed to physiologic overgrowth. The authors recommended advancing the lateral nail into or just distal to the greater trochanter apophysis, and advancing the medial nail into the femoral neck just short of the proximal femoral physis (Fig. 6.4a, b). This modification in technique may increase rotational and angular stability by decreasing the forces across the fracture site. The authors also suggested intraoperative stressing of the fracture after fixation to determine whether postoperative immobilization is necessary [5].

Stainless steel flexible intramedullary nails may be an alternative to titanium elastic nails for treatment of pediatric subtrochanteric femur fractures [19, 40]. Unlike titanium elastic nails, which are not optimal for length-unstable fractures, stainless steel nails have demonstrated good results in the treatment of length-stable and length-unstable pediatric femoral shaft fractures [40]. Distal locking of the stainless steel nail increases rotational control, and may prevent fracture shortening with a subsequent reduction in complications in length-unstable fractures [41]. Stainless steel nails have not been specifically studied in pediatric subtrochanteric femur fractures. The authors' technical tips in flexible intramedullary nailing of pediatric subtrochanteric femur fractures can be found in Table 6.5.

Plating

Plate fixation is an alternative method of fixation in children 5–11 years of age with length-unstable femur fractures, children who weigh more than 49 kg, and children over 11 years who have a femoral canal that is too narrow for rigid intramedullary nailing. Traditional open plating and

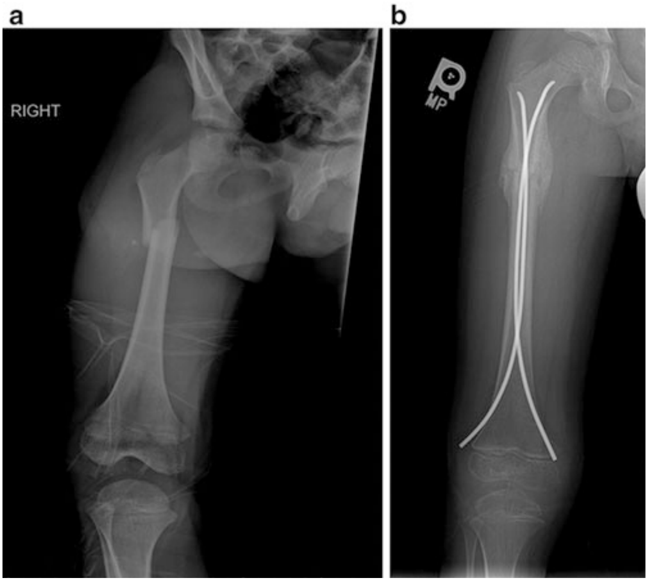

Fig. 6.4 (**a**, **b**) A 4-year-old male who sustained bilateral femur fractures after MVC. (**a**) A right displaced and shortened subtrochanteric femur fracture. (**b**) Patient 6 weeks after flexible nailing of the fracture

Table 6.5 Technical tips for flexible intramedullary nailing

Anesthesia:	General with muscle relaxation.
Position:	Supine on a radiolucent table.
Implant selection:	• Nail size is determined using the following equation: 1 cm is subtracted from the smallest femoral canal diameter measured on preoperative AP and lateral radiographs, and the result divided by 2.
	• This measurement correlates with the size of the individual nails.
	• Alternatively, one can use 40 % of the narrowest canal diameter to determine nail size.
	• Two nails of equal diameter are used in all cases to balance the forces across the fracture site and prevent angular deformity.
Exposure:	• Fluoroscopy is used to locate the nail insertion site, which is 2.5 cm proximal to the distal femoral physis.
	• An incision is made on the lateral aspect of the distal thigh from the level of proposed nail insertion and is carried 2 cm distally.
	• The subcutaneous tissues and IT band are opened in line with the skin incision, exposing the lateral aspect of the distal femoral metaphysis.
	• The lateral cortex is opened with a drill or a sharp awl.
	• The drill or awl is then redirected cephalad so that it makes a 10-degree angle with the lateral cortex.
	• This will allow the nail to glance off the far cortex as it is advanced and facilitate passage of the nail in the canal.

(continued)

Table 6.5 (continued)

Steps:	• A slight bend is placed at the tip of the nail to facilitate advancement of the nail beyond the far cortex and to assist with fracture reduction.
	• The nail is then inserted in the starting hole and the intramedullary position verified using fluoroscopy.
	• If the proximal fracture fragment is significantly displaced, a Steinmann pin can be placed percutaneously into the proximal fragment. The proximal fragment can then be easily manipulated to facilitate fracture reduction.
	• The fracture is reduced and the lateral nail is advanced across the fracture site.
	• Next, a medial incision is made, and a nail of equal diameter is placed and advanced into the proximal fragment.
	• Alternatively, both nails can be inserted up to the fracture site and then advanced sequentially across the fracture, making sure that the nails do not bend.
	• If titanium elastic nails are used, advancement of the tip of the lateral nail into or just distal to the greater trochanteric apophysis, and advancement of the tip of the medial nail into the femoral neck just short of the proximal femoral physis may increase fracture stability.
	• When the nails are approximately 1 cm from their final position, the nails are trimmed outside the skin.
	• Final impaction is then performed with a tamp, leaving 1 cm of nail outside the bone.
	• The nail tip should not be bent away from the cortex to minimize soft tissue irritation.
	• Knee range-of-motion should be checked postoperatively to make sure that the nail tips are not impeding motion.
Postoperative care:	• Supplemental external immobilization, such as a knee immobilizer, may be necessary.
	• Hip and knee range-of-motion exercises can be performed immediately.
	• Toe-touch weight-bearing is advised for 4–6 weeks after surgery.
	• Weight-bearing is advanced when radiographic healing is evident.
	• Nails can be removed at 6–12 months postoperatively.

submuscular plating have been described for the treatment of pediatric subtrochanteric femur fractures [42, 43]. Traditional open plating requires more extensive soft tissue dissection, longer operating times, greater blood loss, and potential disruption of periosteal blood flood, thereby increasing the risk of delayed union or nonunion. In cases where proximal fixation is limited, long oblique fracture patterns or patient-specific anatomic constraints, locking plates allow fixation into the femoral neck, optimizing surgical fixation.

Alternatively, submuscular plating uses a minimally invasive insertion technique. Submuscular plates may function as internal "external fixators." Indirect fracture reduction and increased biomechanical stability can be obtained with longer plates and fewer screws. The increased working length of a long plate leads to decreased strain on the construct and reduced pull-out force on the screws. Similar to placement of an external fixator, one screw should be placed just proximal and one screw should be placed just distal to the fracture. The remaining screws should be spread wide apart for maximum stability. For subtrochanteric femur fractures, the plate is inserted through a proximal incision over the lateral thigh. The plate is then advanced extraperiosteally between the lateral femur and vastus lateralis in a proximal-to-distal direction. Subtrochanteric femur fractures may be better stabilized with a locking plate. There is biomechanical evidence that locking plates provide more stable fixation than titanium elastic nails in femur fractures (Fig. 6.5a, b) [44, 45].

Kanlic et al. evaluated 51 pediatric femur fractures treated with submuscular plating, 24 % of which were in the subtrochanteric region. No postoperative immobilization was used. All of the fractures healed. No wound healing problems or infections were found. Eight percent of patients had a leg length inequality with the affected limb

Fig. 6.5 (**a**, **b**) A 9-year-old male who fell while skiing. (**a**) The patient sustained a right displaced oblique subtrochanteric femur fracture. (**b**) Patient 6 months following submuscular plating

ranging from 23 mm shorter to 10 mm longer. However, none of the patients with subtrochanteric femur fractures experienced significant complications (Table 6.6) [46].

Rigid Intramedullary Nailing

Subtrochanteric femur fractures have been treated successfully with rigid intramedullary nailing in the adult population. These fractures may also be managed in adolescents using nails with a trochanteric entry point or lateral trochanteric entry point. Subtrochanteric femoral fractures have a short proximal fragment with a wide medullary canal, making standard locking techniques potentially inadequate to secure the short proximal fracture fragment. The wide medullary canal in the proximal femur increases the risk of the nail toggling due to lack of screw purchase; therefore, when appropriate a cephalomedullary nail should be used, because its screws engage the bone in the femoral neck. Malalignment of the proximal fragment may occur despite placement of the nail, which may be avoided by assuring an anatomic alignment and control of the proximal fragment during the procedure. The reconstruction femoral nail has a widened proximal section that incorporates one or more interlocking screws, designed to be placed into the femoral neck. While not directly applicable to the pediatric population, a Cochrane Database review of 189 adults with subtrochanteric femur fractures found that intramedullary nails were associated with fewer fracture fixation complications and higher healing rates than fixed angle plates [47]. Rigid intramedullary nailing can be safely performed in children 11 years to skeletal maturity with a subtrochanteric femur fracture using a trochanteric or a lateral trochanteric entry point, provided the femoral canal is large enough to accommodate the nail [48–50]. A more recent study suggests that children aged 7–12 years may also be acceptable candidates for such newer lateral-entry nailing techniques [51]. The main technical difference between pediatric and adult rigid intramedullary nailing is in the starting point of the femoral nail. A piriformis starting point in a skeletally immature patient places the posteriorly based medial femoral circumflex vessels at risk, injuries to which could lead to avascular necrosis of the femoral head, a rare, but serious, complication. MacNeil et al. performed a systematic review of 19 articles and found an avascular necrosis rate of 2 % when the nail was inserted from the piriformis fossa, compared to 1.4 % from the tip of the greater trochanter, and no reported cases from the lateral aspect of the greater trochanter (Fig. 6.6a, b) [52] (Table 6.7).

Outcomes and Complications

There are few reports in the literature on the outcomes and complications of treatment of pediatric subtrochanteric femur fractures. Complications are related to the strong deforming muscle forces acting at the fracture site and the treatment method. The risk of various complications for each treatment method is listed in Table 6.8.

Flexible Intramedullary Nailing

Titanium elastic nails are currently accepted as the preferred treatment for femoral shaft fractures in children 5–11 years of age; however, they have

Table 6.6 Technical tips for open and submuscular plating

Open plating	
Anesthesia:	General with muscle relaxation.
Position:	Supine on a radiolucent table with a soft bump under the ipsilateral flank.
Implant selection:	• The plate is selected according to the size of the femur.
	• 3.5 mm or the 4.5 mm narrow stainless steel low-contact dynamic compression plate or proximal femoral locking plate.
	• Anatomic constraints of the proximal femur may necessitate plate contouring.
	• Depending on the fracture pattern and extent of comminution, plates with eight or more holes are chosen.
Exposure:	• A straight lateral incision is made over the fracture site and dissection carried down through the iliotibial band.
	• The vastus lateralis is retracted anteriorly, and care is taken to identify and ligate the perforating arteries and veins.
Steps:	• The fracture is reduced under direct visualization and held with a bone clamp.
	• Independent lag screws are inserted if lag screw application through the plate is not possible.
	• The goal is to get six cortices above and below the fracture.
	• If a locking plate is used, a fully threaded cortical screw is used to bring the plate to the bone. Fixed angled locking guides are then screwed into the plate to give the appropriate trajectory for the locking screws.
	• When possible bicortical screw fixation should be performed.
Postoperative care:	• No supplemental external immobilization is necessary.
	• Hip and knee range-of-motion exercises can be performed immediately.
	• Toe-touch weight-bearing is advised for 6–8 weeks after surgery.
	• Weight-bearing is advanced when radiographic healing is evident.
Submuscular plating	
Anesthesia:	General with muscle relaxation.
Position:	Supine on a radiolucent table or fracture table.
Implant selection:	• A 4.5 mm narrow stainless steel low-contact dynamic compression plate is appropriate for most patients. A proximal femoral locking plate can also be used.
	• The length of the plate is determined with the use of fluoroscopy.
	• The average plate length is 12–16 holes to allow for greater distance between the screws.
	• The plate is contoured to match the proximal metaphyseal flare.
Exposure:	• A 3 cm incision is made over the lateral aspect of the proximal femoral metaphysis and the iliotibial band is split.
	• The vastus lateralis is elevated anteriorly.
	• A Cobb elevator is passed extraperiosteally deep to the vastus lateralis to create a tunnel for the plate.
Steps:	• The plate is inserted into the submuscular interval. • Traction is applied to the extremity to maintain fracture length and the plate is advanced distally under fluoroscopic guidance. • Fluoroscopy is used to verify plate position and reestablishment of fracture length.
	• The plate is provisionally secured with Kirschner wires in the most distal and most proximal screw holes.
	• Insertion of an additional Kirschner wire through the middle of the plate can correct procurvatum at the fracture site.
	• The first screw is placed through the proximal incision. The remaining screws are placed percutaneously.
	• Indirect fracture reduction can be achieved by placing the second screw just proximal or distal to the fracture, where the femur is farthest from the plate.
	• The perfect circle technique on lateral fluoroscopy can assist with percutaneous screw placement.
	• The screws can be tagged with absorbable suture to assist with screw exchange if necessary.
	• Three screws proximal and distal to the fracture placed far apart provide adequate stability. No lag screws are necessary.

(continued)

Table 6.6 (continued)

Postoperative care:	• No supplemental external immobilization is necessary.
	• Hip and knee range-of-motion exercises can be performed immediately.
	• Toe-touch weight-bearing is advised for 6–8 weeks after surgery.
	• Weight-bearing is advanced when radiographic healing is evident.
	• Although implant removal in children remains controversial, there is evidence that patients with distal femoral shaft fractures treated with open or submuscular plating and plates that are placed ≤20 mm from the distal femoral physis are at risk of developing a distal femoral valgus deformity that may require further surgical intervention. [56]
	• Plates can be removed at 6 months postoperatively.
	• Removal of submuscular plates can be complicated by bony overgrowth at the tip of the plate, which may require more extensive exposure to remove the ingrown bone.

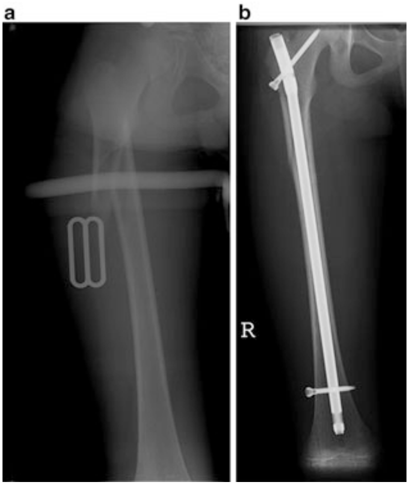

Fig. 6.6 (**a**, **b**) A 10-year-old female who fell while snow skiing. (**a**) Displaced and angulated subtrochanteric femur fracture. (**b**) 1 year following cephalomedullary femoral nailing of fracture through a trochanteric entry point

also been shown to be associated with a number of complications with fractures in the subtrochanteric region [16, 19, 20]. In fact, it was shown that almost a quarter of patients with proximal third femur fractures treated in such a way experienced complications [19]. Typically, those complications resulted from fracture displacement, and include leg-length differences, malunion, or irritating hardware [16–20, 53]. A need for additional surgery has been identified as a complication in children and adolescents with length-unstable fractures managed with titanium elastic nails [17, 18].

Narayanan et al. demonstrated that comminuted fractures had a five times greater risk of loss of reduction leading to reoperation or malunion. Pediatric subtrochanteric femur fractures usually result from a high-energy mechanism of injury, which is more likely to produce an unstable fracture pattern. If titanium elastic nailing is selected as the treatment method, the lateral nail should be advanced into or just distal to the greater trochanter apophysis, and the medial nail should be advanced into the femoral neck just short of the proximal femoral physis. Pombo and Shilt reported no major complications and no poor results in their series of 13 pediatric patients with subtrochanteric femur fractures treated using this technique [5]. However, fracture stability should be assessed intraoperatively after fixation, and postoperative immobilization with a single-leg spica cast, hip-knee-ankle-foot orthosis, or knee immobilizer should be considered if residual instability is found.

Plating

Caird et al. reviewed 60 pediatric patients with femoral shaft fractures treated with open plating. Twenty-five percent of the fractures were in the proximal third of the femur. The overall complication rate was 10 %, which included one early implant failure, two refractures after the plate was removed, two symptomatic leg length inequalities, and one hypertrophic scar. Four of these patients required unplanned surgery. Three of the six complications occurred in fractures of the proximal third of the femur [54].

In a multicenter retrospective study, Li et al. compared titanium elastic nailing with plating

Table 6.7 Technical tips for rigid intramedullary nailing

Anesthesia:	General with muscle relaxation
Position:	Supine on a fracture table or lateral on a radiolucent table.
Implant selection:	Pediatric cephalomedullary femoral nail with a lateral trochanteric entry point
Exposure:	• A true AP radiograph of the proximal femur must be obtained prior to guide pin placement, which is accomplished by internally rotating the extremity.
	• The starting point is just lateral to the tip of the greater trochanter in the AP plane, and at the junction of the middle and posterior thirds of the femoral neck in the lateral plane.
Steps:	• Guide pin placement is percutaneous and can be initiated using a mallet to prevent inadvertent plunging into the piriformis fossa.
	• The guide pin is advanced using power to the level of the lesser trochanter.
	• An entry reamer is then utilized to initiate the starting hole for subsequent placement of the guide rod and intramedullary nail.
	• It is critical that adequate reduction of the subtrochanteric femur fracture is obtained prior to reaming to avoid malalignment following nail placement. If the proximal fracture fragment is significantly displaced, a Steinmann pin can be placed percutaneously into the proximal fragment. The proximal fragment can then be easily manipulated to facilitate fracture reduction.
	• Ream 1–1.5 mm greater than the diameter of the nail.
	• Proximal interlocking is performed with a screw placed percutaneously into the femoral neck using the guide. This screw should stop short of the proximal femoral physis if the physis is open.
	• Distal interlocking is carried out with one to two screws placed freehand using the perfect circle technique.
	• The addition of a second distal screw enhances the rotational stability of the construct and is important in unstable fractures [57].
Postoperative care:	• No supplemental external immobilization is necessary.
	• Progressive ambulation to full weight-bearing is encouraged, unless extenuating circumstances prevent adequate fracture fixation.
	• The nail can be removed at 12 months postoperatively.
	• Skeletally mature or near-mature patients do not routinely need to have their implants removed.
Other:	• Increased risk for internal rotation fracture malalignment when performed on a fracture table [58]. Use the patella to gauge rotation.
	• During interlock placement, it is important to make sure that the patella is facing the ceiling to obtain neutral alignment.

Table 6.8 Reported complications by treatment method

	LLD	Skin necrosis	Prominent implants	Infection	Malunion	Malrotation	Nonunion	Nerve injury
Hip spica cast	+	+	–	–	++	++	–	+
External fixation	+	–	–	+++	+	+	+	+
Flexible nails	+	–	++	+	++	++	+	+
Open plating	+	–	+	+	–	+	+	–
Submuscular plating	+	–	+	+	+	+	+	–
Rigid nails	+	–	+	+	–	++	–	–

LLD leg length discrepancy, + mild risk, ++ moderate risk, +++ high risk

Table 6.9 Comparison of complications of titanium elastic nailing and plating

	Titanium elastic nails	Plating	*P*
Fracture malalignment	4	1	–
Leg-length inequality	4	3	–
Pain from prominent implants	3	3	–
Knee stiffness	1	0	–
Cellulitis at insertion site	1	0	–
Saphenous nerve paresthesias	1	0	–
Skin maceration from cast	1	0	–
Total patients with complications	12[a] (48 %)	4 (14 %)	0.008

Adapted from Li Y, Heyworth BE, Glotzbecker M, et al. Comparison of titanium elastic nail and plate fixation of pediatric subtrochanteric femur fractures. J Pediatr Orthop 2013;33:232–8

[a] Three patients had more than one complication

for the treatment of subtrochanteric femur fractures in 54 school-aged children. The authors found that patients treated with titanium elastic nails had a significantly higher overall complication rate than patients treated with plating (48 % versus 14 %), but the major complication rate was similar (Table 6.9). Outcome scores were also significantly better in the plating group than in the nail group, but both groups had high rates of excellent and satisfactory results (97 % and 92 % respectively). Length of hospitalization and time to radiographic union were comparable between the two groups. Plating technique did not appear to influence the complication rate and outcome, as the open plating and submuscular plating groups demonstrated similar results [20].

Conclusion

Subtrochanteric femur fractures are rare in the pediatric population, and are a challenge to treat. There is a lack of agreement on the definition of a subtronchanteric fracture in this age subset, and a dearth of literature evaluating treatment outcomes. Despite the lack of definitive treatment algorithms, there are some guidelines that should be followed. It is important to keep age and body size in mind when choosing a treatment option. The unique biomechanics around the subtrochanteric region and the torsion forces leading to injury are different than those seen in mid-shaft fractures, so must be taken into consideration. Corresponding injuries, fracture pattern, and rotational deformity are also important in determining the best course of care, and can be assessed through history and radiological examination. Pavlik harnesses are recommended for use in children 0–6 months of age. Spica casting is an acceptable form of treatment in children 6 months to 5 years of age with stable fractures. If the fracture is deemed too unstable, operative measures may be reasonable to pursue in this younger age group. The method of treatment in patients aged 5–11 years old is dependent upon stability, with flexible intramedullary nailing acceptable for stable fractures and open or submuscular plating viable options for more unstable fractures. Children aged 11 years to skeletal maturity are usually treated with rigid intramedullary nailing using a trochanteric or lateral trochanteric entry site. Finally, external fixation should be reserved for children with open fractures, polytrauma patients, and fractures with associated neurovascular injuries. There are complications and risks associated with all treatments, which should be discussed with the patient and family when considering the various care options.

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Treatment of Pediatric Diaphyseal Femur Fractures: Spica Casting and Traction

7

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and Michael G. Vitale

Introduction

Femoral shaft fractures in children account for between 1 and 2 % of all pediatric fractures and the most common traumatic musculoskeletal injury requiring inpatient care [1–4]. This common fracture can be treated in a variety of different ways depending on patient age, fracture pattern, and associated injuries. Recent trends in treatment of femoral shaft fractures in the pediatric population have shifted away from cast application and traction in favor of operative intervention. Despite this transition over the last decade, there remain a large number of patients who would benefit from a more conservative, nonoperative approach. In this chapter we examine the history of traction and application of hip spica casts and argue for continuation of these traditional forms in the treatment of certain pediatric femoral shaft fractures.

Classification of Femoral Shaft Fractures in Children

There are several commonly utilized classification systems for femoral shaft fractures in pediatric patients. It should be noted that none of the described classification systems are widely used or embraced by the pediatric orthopedic community. In considering fractures of the femoral shaft, anatomic location of the fracture is extremely important with significant implications for treatment. Fractures of the femoral shaft can be thought of as diaphyseal, subtrochanteric, or supracondylar. It is essential to recognize subtrochanteric femur fractures, as these pose unique treatment challenges. With subtrochanteric fractures, there are strong muscular forces acting on the proximal fragment which are difficult to overcome when reducing the fracture. One set of muscles act to flex, abduct, and externally rotate the proximal fragment, while others adduct and apply proximal forces on the distal fragment, all of which make fracture reduction difficult. There are several conflicting definitions of subtrochanteric fracture in the pediatric population. For example, some define it as any fracture line within 3 cm of the lesser trochanter or involving any part of the proximal third of the femur, but children can have a wide range of femoral lengths and sizes even at the same age [5, 6].

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Pombo described a new classification system that is dynamic and makes adjustments for the growing child [7]. Using the accepted adult classification, which defines a subtrochanteric fracture to be within 5 cm of the lesser trochanter, Pombo et al. referenced work that defined an average adult femur length at 45.23 cm and calculated that 5 cm divided by 45.23 cm is 11 % of the total length of the femur [8]. For simplicity, the authors rounded down to 10 % and classified a pediatric subtrochanteric fracture as one with the fracture line extending to a distance within 10 % of the total femur, measured from the lesser trochanter.

Identifying a supracondylar femoral shaft fracture is also important because of the deforming forces pulling on the distal fragment. These deforming forces include the hamstring tendons, which may flex the distal fragment, or the gastrocnemius muscles, which may instead extend the distal fragment. A supracondylar femur fracture may be defined as one in which the distance from the lowest point of the fracture to the center of the knee joint is less than or equal to the width of the femoral condyles at their widest point [9]. Adjustments in treatment plan will need to be considered in the treatment of the more challenging subtrochanteric and supracondylar femur fracture types.

Other authors recommend classifying femoral shaft fractures by fracture pattern—either transverse, spiral, or oblique—and whether the fracture is comminuted or not. The AO Foundations's Pediatric Long Bone fracture classification system is gaining more widespread use (Table 7.1). The femur is identified in the AO system with the number 3 (in contrast to humerus, which is 1, radius/ulna, 2, and tibia/fibula, 4). The second number in the AO classification system is to identify the location in the femur of the fracture, with the diaphysis as the second segment (2), while the first (1) segment is proximal and is divided into (E) epiphysis and (M) metaphysis, and the third (3) segment is distal and also subdivided into (M) metaphysis and (E) epiphysis.

Table 7.1 The pediatric AO fracture classification outline

Diagnosis				
Localization			Morphology	
Bone	Segments	Subsegments	Child	Severity
1 2 3 4	1 2 3	E M D	1–9	.1 .2

The patterns to further describe pediatric fractures for a diaphyseal femur segment include (D/1) bowing fractures, (D/2) greenstick fractures, (D/3) toddler fractures, (D/4) complete transverse fractures, (D/5) complete oblique/spiral, or (D/9) any other diaphyseal fracture pattern. The final additional number for this classification is to describe fracture severity. For simple and wedge-type fractures a (.1) is added to the end, while complex fractures with more than three fragments receive a (.2) addition. For example, a transverse pediatric diaphyseal femur fracture would be classified as a 32-D/4.1 (3-femur, 2 location of diaphysis, D/4 for transverse, and .1 for simple fracture pattern).

The Gustilo and Anderson Classification system is utilized to further subcategorize open femur fractures [10]. A type I involves a clean wound less than 1 cm. Type II open fractures involve a wound greater than 1 cm with moderate associated soft-tissue injury. Type III fractures are extensive wounds usually greater than 10 cm with damage to skin and soft tissues. These can be associated with high-velocity or crush injuries. A few other special situations qualify as type III injuries, regardless of wound size. These include traumatic amputations, high-velocity gunshot wounds, and farm injuries with contamination and open segmental fractures. There are also subtypes of these fractures. Type IIIA fractures convey adequate soft-tissue coverage, and type IIIB have extensive periosteal stripping and bone exposure and are often contaminated. Type IIIC injuries are associated with a major arterial injury.

It should be re-emphasized that none of the classification systems mentioned above receive widespread use by the pediatric orthopedic community, with the exception of the Gustilo and Anderson Classification for open fractures. While there is no universally accepted classification system at this time, most surgeons make treatment decisions based on description of the fracture pattern, the fracture location, soft-tissue injury, and any other associated injuries.

History of Traction

Since the times of the ancient Greeks, traction has been utilized to reduce dislocations and splint fractures. Some inventive devices, complete with pulleys, levers, and ropes, were used to treat fractures in ancient times. The first use of continuous, isotonic traction to treat a fracture was credited to Guy de Chauliac (1300–1368), a French surgeon more famous for his work combating the Black Plague [11]. Using Hippocrates' teachings that fractures of the femoral shaft should be treated in extension, a weight was suspended attached to a cord over a pulley at the end of the bed. The weight was attached to the leg using a handkerchief (Fig. 7.1a, b). For prolonged treatment of femoral shaft fractures, this treatment approach had significant shortcomings. The chief problem was how to attach the traction device to the limb without causing sores or problems of hygiene related to the prolonged position in bed. Attachment of the weight using a handkerchief was acceptable for isometric traction, but insufficient for continuous isotonic traction.

Percivall Pott (1714–1788) challenged the teachings of his time and refuted Hippocrates' dictum to treat femoral shaft fractures in extension [11]. He argued that the primary cause of deformity and malunion after femur fractures resulted from the forces and pull of the surrounding thigh muscles. He advised placing the limb in a position that relaxed these deforming forces. Pott recommended flexing the hip and knee and his original description describes the limb lying on its side (Fig. 7.2) [12]. Unfortunately, Pott's design was difficult to maintain for the prolonged time necessary to treat these fractures in traction. A modification to his principles was made by Robert Chesser, who advocated supine positioning of the patient with the leg in a double-inclined plane (Fig. 7.3) [11]. This modification allowed Pott's principles of hip and knee flexion to be applied in a practical setting.

Femoral shaft fractures continued to be treated in this fashion until the middle of the nineteenth century, when the results of current treatments were challenged by one of the leaders of American orthopedic surgery, Franklin Hastings

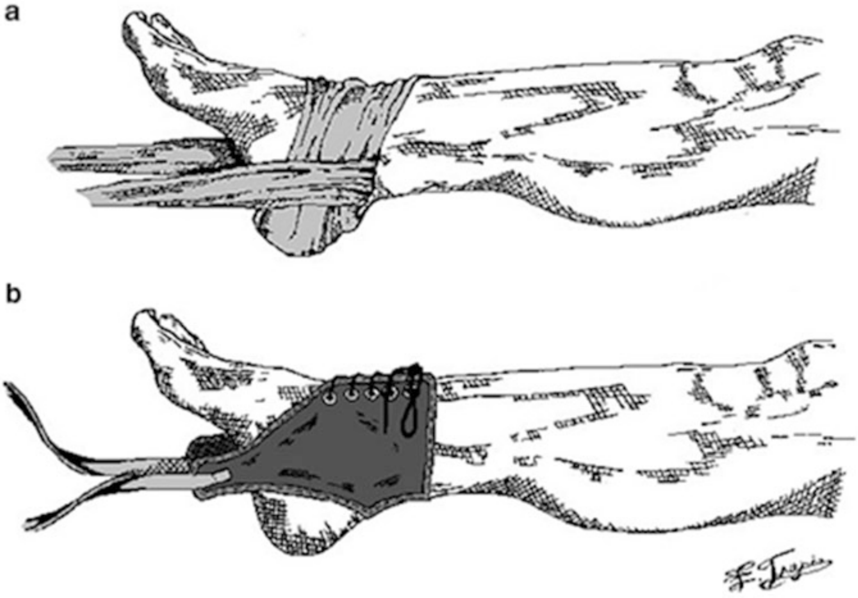

Fig. 7.1 (**a**, **b**) The handkerchief and the gaiter were the usual methods of applying traction to the leg in the eighteenth century

Hamilton. Hamilton reviewed the treatment of a multitude of different fractures in his famously recorded fracture tables [11]. On careful review of current treatment with traction for femoral shaft fractures, he found only 9 of 83 fractures to have a "perfect" result. His scrutiny prompted the orthopedic community at the time to rethink the treatment of this fracture and discover that more effective ways were needed to overcome the forces of the large thigh muscles. Two different strategies were employed to improve their methods. The first strategy was the development of the traction splint. The second strategy focused on improving the attachment of the traction to the limb itself. This reevaluation led to advances in skin and skeletal traction.

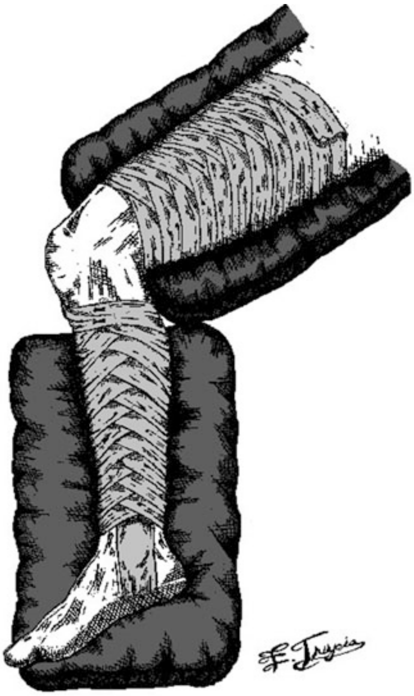

Fig. 7.2 Pott's method of treatment

The use of splint traction was developed by Nathan Smith (1762–1829), who was thought of as one of the great American surgeons of his time [13]. His technique involved placing a well-padded splint to the limb with the hip and knee flexed and then attaching a cord to the splint. The cord then passed through a pulley and was secured to a weight. Other surgeons modified Smith's original design. John T. Hodgen, a surgeon from St. Louis, made additional modifications to the pulley and the splint. The Hodgen's splint was introduced for gunshot wounds of the femur and was used to treat injuries during the Civil War and in Europe during World War I (Fig. 7.4) [14].

Throughout the history of medicine, many eponyms have been attributed to individuals who were not actually the first to describe an operation or technique [15]. For instance, *Buck's traction* is an example of an eponym incorrectly associated with someone other than the original creator of the technique. Gurdon Buck, a general surgeon who resided in New York, initially popularized skin traction. He published his results in 1861 on the treatment of 21 femoral shaft fractures with a method of skin traction [16]. However, the technique he described in this paper was originally devised by Josiah Crosby, who

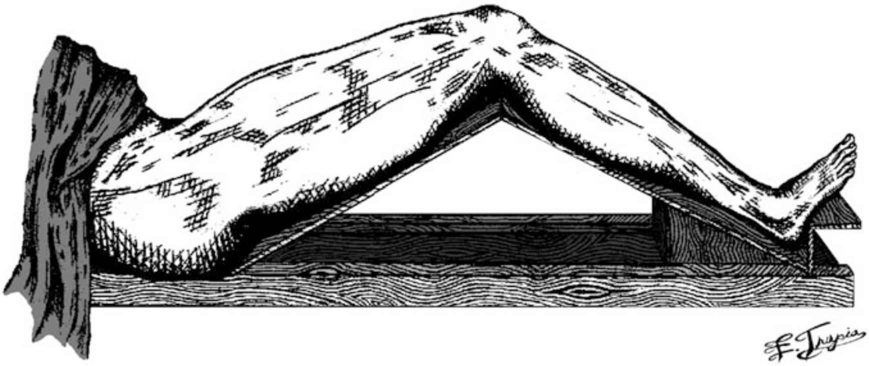

Fig. 7.3 Chesser's double incline

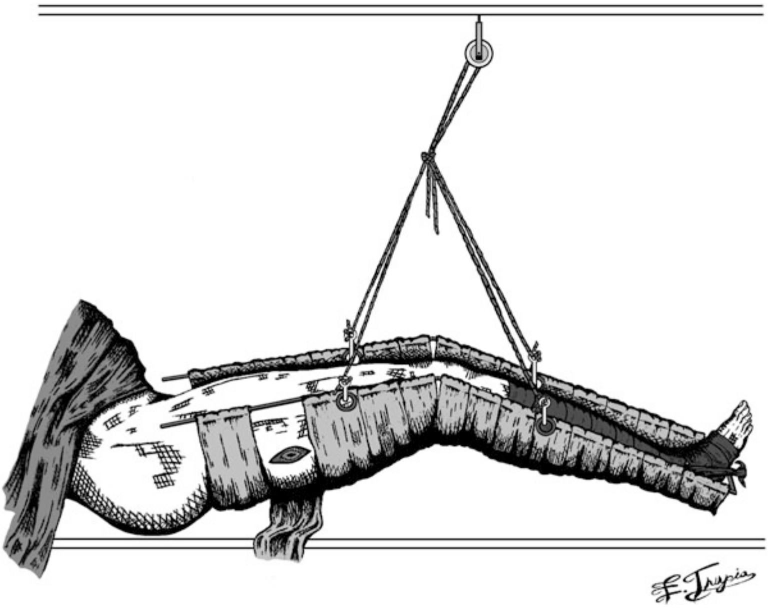

Fig. 7.4 Hodgen's splint

was the first to publish and promote the use of isotonic skin traction [17, 18]. Buck's traction, as it is now known, saw widespread use during the Civil War. It proved to be so popular that awareness of the technique traveled overseas to Europe, where it was referred to as the "American Method" [19].

An Australian surgeon, R. Hamilton Russell, developed a method to utilize both the benefits of isotonic skin traction with those of maintaining knee and hip flexion (usually around 20–30°) [20]. Incorporating a system of four pulleys and a gentle sling under the knee, it remains a popular choice for placing femur fractures in traction. Some key differences from previous setups include the number of pulleys required and the positioning of the ipsilateral thigh and knee. The skin adhesive does not extend above the knee. There are two vectors of pull, and the resultant line of traction on the femur allows for more than twice the amount of the weight used for other forms of traction [21]. This method (Fig. 7.5) remains the current preferred approach for long-term treatment of femoral shaft fractures with the use of isotonic skin traction, when such indications arise.

While the improvements in techniques of skin traction seen during the eighteenth and nineteenth centuries represented steps in the right direction, there were continued disadvantages of these methods. In certain patients, skin traction alone was not enough to overcome the deforming forces in the muscular thigh, and cases of malunion persisted. In addition, in 1895 a German professor of physics, Dr. Wilhelm Konrad Roentgen, invented the radiograph [22]. With X-rays gaining acceptance, new criteria were available to judge and grade the results of different treatments for femoral shaft fractures. It soon became apparent that improved traction methods were needed.

Interest in skeletal traction—in which direct attachments are made between the bones and the traction device through wires, pins, or screws—was rekindled around the turn of the century, with a variety of European surgeons promoting its use. Two Italian surgeons, Giuliano Vanghetti and Alessandro Codivilla, as well as a German contemporary Fritz Steinmann, all separately described techniques of applying pins and wires into the bone to treat fractures of the femur in the early twentieth century [19]. By the time of World War I, skeletal traction had become commonly utilized in treating femoral shaft fractures. Among the different techniques, 90–90 distal femoral traction is among those warranting

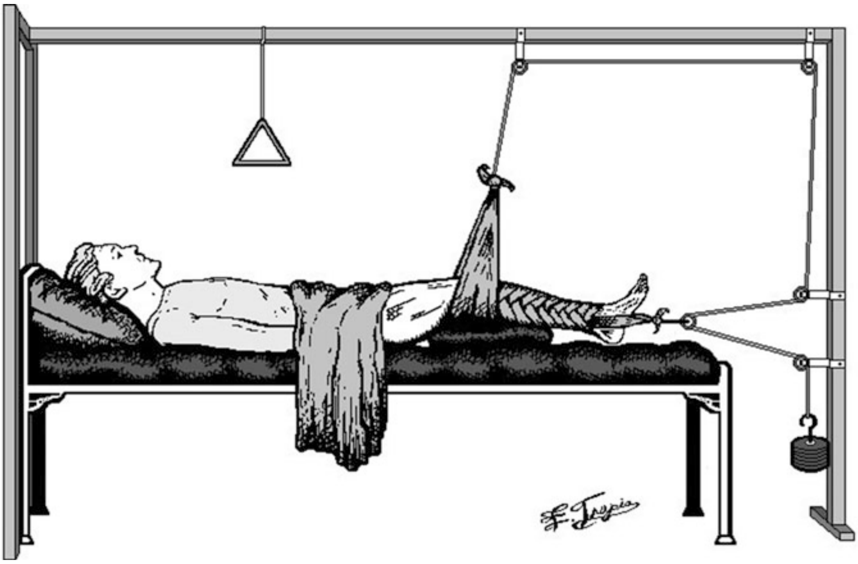

Fig. 7.5 Russel's traction setup. Note the flexion of the hip and knee

description. With the pin in the distal femur, the thigh is suspended in a vertical plane by the upward pull of the traction. This type of setup eliminates the effect of gravity on fracture shortening. The hip and knee are both flexed to 90°, and weights are applied to the traction pin or bow with a pulley system [23]. Either a sheepskin sling or a short leg cast can be used to balance the lower leg. This traction is used until initial callus forms, and the patient can then be transitioned to a hip spica.

While many of the above techniques for treating femoral shaft fractures were applied to children, until the middle of the nineteenth century, the prevailing strategy for treating most pediatric femoral shaft fractures could best be described as "benign neglect." An excerpt from a medical journal in the mid-nineteenth century exemplifies this attitude:

> If all apparatus be dispensed with, and the child be only laid on a firm bed, with little or no head pillow, and with the broken limb, after setting it, bent at the hip and knee, and laid on its outer side, there it will remain. [24]

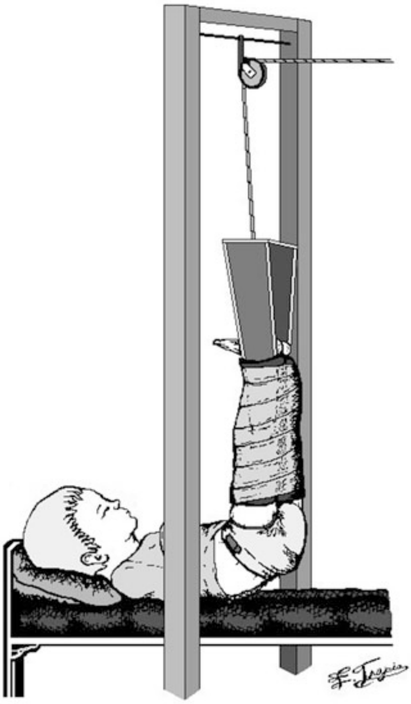

Fig. 7.6 Gallows traction

In 1872, British surgeon Thomas Bryant advocated for a different approach for treatment of femoral shaft fractures in children [25]. Also known as "Gallows traction" (Fig. 7.6), Bryant promoted a method that utilizes skin traction to suspend the child's buttocks off the bed surface. The child's legs are wrapped together and lightly splinted. The body then serves a constant counter-extending force. Excellent results using this method have been described for children less than 4 years of age [26].

Present-Day Use of Traction

Traction for the treatment of femoral shaft fractures has a detailed and storied history in the development of the field of orthopedic surgery. The use of traction continues to have a place in the closed treatment of femoral shaft fractures. In most instances in the USA, traction is used as a bridge to more definitive treatment methods for these fractures. Many times utilized to optimize patient comfort, short-term traction is applied until the patient can be taken to the operating room for surgical treatment or hip spica casting. However, there is some debate as to which type of traction to use. Many centers advocate skeletal traction to maximize distraction of the muscles and to keep the fracture out to length. Skin traction, on the other hand, is generally favored for avoiding the invasiveness, pain, and sedation requirements of skeletal traction, but is limited by the amount of weight that can be utilized, because of concerns regarding skin breakdown and vascular compromise. Interestingly, a recent study looking at narcotic use in patients undergoing skin or skeletal traction for isolated femoral shaft fractures in children aged 4–14 found no difference in pain medication use over the first 24 h [27]. This study suggests that the more invasive skeletal traction may not provide substantial benefit over skin traction, with regard to pain control, before definitive treatment of isolated femur fractures.

Advocates of skeletal traction will point out that it does an excellent job of keeping the soft tissues out to length and can make the definitive procedure or casting much easier to perform. When considering skeletal traction, the most important thing is to determine the location of the traction pin, which may be either the distal femur or proximal tibia, precluding a distal femoral pin. There are concerns with proximal tibia pins. Because proximal tibial pins can cause damage to the proximal tibial physis if placed incorrectly, and it can be harmful to pull traction across a knee with a ligamentous or meniscal injury, we favor distal femoral pins, unless there is significant soft-tissue compromise around the distal femur. An ipsilateral tibia fracture is also a contraindication to a proximal tibia traction pin.

Skin or skeletal traction in a child with a femur fracture is considered in the following situations: (1) an unstable fracture with more than 2 cm of shortening; (2) a fracture that fails to maintain length in a hip spica cast in a child under 6 years of age; (3) a polytrauma patient who is unable to go expeditiously to the operating room for definitive treatment; and (4) for a patient less than 10 years old (and size under 100 lb) without soft-tissue injury or associated injuries, able to be compliant with prolonged bedrest and eventual spica placement, for a family that is adamant about avoiding more invasive surgery.

Skin traction can be an attractive option in certain situations. We recommend no more than 5 lb be utilized, because of concerns of skin sloughing and blistering. To determine the weight needed for traction, we use the general rule of 10 % of body weight. If more than 5 lb of traction is required, we recommend utilizing skeletal traction pins instead.

There is a body literature supporting the use of skin traction, followed by placement of a hip spica cast for the management of femoral shaft fractures in children aged 4–10 years of age. In one paper from San Antonio, 41 children were treated with skin traction for a mean of 21 days before conversion to a hip spica cast for 9.7 weeks. The mean age of the children in the study was 6.5 years and they were followed for more than 2 years. The authors reported no significant leg length difference or angular deformity. While cost of this method was not evaluated in the study, skin traction followed by delayed hip spica is a viable treatment option for the right patient [28]. Another study from Singapore by Lee et al. also studied treatment with traction followed by delayed spica casting, with similar results [29]. The mean age in the study was 5.3 years with a range up to 15 years old. The authors noted a leg length discrepancy after treatment in 22 % of patients. However, none of these discrepancies exceeded 1.5 cm and none resulted in a short-legged gait. The patients had no cases of malunion, loss of reduction requiring recasting, or skin complications.

In North America, however, reduced reliance upon traction preceding hip spica treatment may relate less to differences in the outcomes of treatment and more to differences in cost, hospital length of stay, and resources required to implement this treatment approach successfully [1]. Economic forces at work in the US healthcare system have put a premium on shortening length of stay and cost to both hospitals and society, all of which may be significant drivers of trends towards more operative treatment and immediate spica casting over traction methods.

The evidence elucidating the optimal treatment of diaphyseal femur fractures in the 6- to 12-year-old age group remains a work in progress. In general, traction and hip spica casting are now rarely pursued for children in this age group for two reasons. First, as the child gets larger and approaches 100 lb, the care and burden on the family are significant and should not be minimized. In addition, for preadolescent and adolescent, maintaining the knee in a position close to 90° for an extended period of time is a real risk factor for arthrofibrosis [29]. Achieving an acceptable radiographic result is also more difficult. Maintaining fracture reduction in the cast against larger and stronger deforming forces in school-aged children can lead to higher rates of malunion. For example, in a randomized controlled trial by Wright et al. in *Lancet*, children with a mean age of 6.4 years (range 4–10 years) were randomized to either hip spica or external fixation in the treatment of diaphyseal femur fractures [30]. The hip spica group had a statistically significant increase in the number of defined malunions at 2-year follow-up. RAND physical function scores and satisfaction were similar in the two groups. This study highlights some of the potential limitations of the traction and spica approach in the school-aged child. In this 6–12 age group, we consider elastic nailing, external fixation, and submuscular plating as the best potential treatment options. Recent evidence suggests that rigid, locked intramedullary nailing of fractures may also be acceptable in the age group, given that newer lateral-entry and trochanteric-entry nails may not share the same risks of avascular necrosis with traditional nailing techniques [31–33]. There are numerous factors to consider besides age which include patient weight, additional injuries, fracture pattern, and soft-tissue status. Please see the additional chapters in this book for a more in-depth discussion on these treatment options.

Technique Tips for Insertion of a Distal Femoral Traction Pin

The child should be appropriately sedated, with the help of the emergency room physician or anesthesiologist. A still, sedated patient is essential for the safety and accuracy of pin placement in the distal femur. We prefer to use Betadine prep and prepare the thigh circumferentially from the knee to mid-thigh. There are useful landmarks to ensure that the physis is not injured with placement of the pin. As a good general rule, the distal femoral physis correlates with the position of the center of the patella. Therefore, we recommend placing the pin one fingerbreadth above the patella (mark this with the knee extended). Another helpful landmark can be to place the pin just above the flare of the distal femur. Until one is experienced with the placement of these pins, we recommend using fluoroscopy to verify your location safely above the physis.

Once the location of the pin has been determined proximally to distally, the surgeon palpates the medial side of the femur to find the midpoint of the bone. A small incision is made with a 15 blade at this point and then a hemostat is used to spread down to bone. The pin is then loaded in the drill and is directed medial-to-lateral to avoid injury to the femoral artery as it traverses out of Hunter's canal. The pin should be directed as parallel to the joint of the knee as possible as it goes medial to lateral through the bone. An inappropriately angled pin can direct the distal femur into varus or valgus, which is suboptimal for vector of pull. We recommend using anywhere from a 3/16- to 3/32-in. Steinmann pin depending on the size of the patient. Once the pin starts to tent the skin on the lateral side of the femur, another small incision is made with a 15 blade, and then the pin is advanced far enough to allow for placement of the traction bow. The sharp end of the pin is cut off from the lateral end of the femur and then covered with a pin cap or gauze. We wrap a small amount of Xeroform™ (Covidien, Mansfield, Massachusetts) around the pin-skin interface on each side of the femur. At this point we recommend placement of a short leg cast with a ring or loops to support the leg. Other techniques for employing 90–90 traction involve using a sling to support the leg instead of a short leg cast. If this method is selected, routine and daily stretches of the Achilles tendon need to be performed to prevent contracture.

Pearls

- In young patients who are less cooperative, the importance of adequate sedation and copious local anesthetic cannot be emphasized enough.
- Pin placement must avoid the physis. We recommend placing the pin using fluoroscopy if inexperienced with this technique.
- Our recommendation is to use threaded pins instead of smooth. The threads provide additional stability. The disadvantage of the threaded pins is the slightly higher rate of skin problems.
- Spend time making sure that you are parallel to the knee joint when placing the pin in the femur. It has been shown in a study that obliquely placed pins can cause varus or valgus angulation of the fracture if using traction as treatment until placement of hip spica [34].
- Make sure to cover the ends of the pin well to prevent other healthcare providers from injuring themselves while caring for the child.

History of the Hip Spica Cast

The word spica is derived from Latin *spīca virginis*, which means an ear of grain, usually wheat. The term spica when applied to a cast describes the pattern with which the bandages or plaster are rolled over the injured body part. The pattern required that the turns of the bandage crossed over one another suggested the head of wheat [19]. The great Roman physician Claudius of Galen (130–200 AD), the doctor of the gladiators, wrote about spica bandages in *De Fasciis liber* (Book on Bandages) [35]. He is also referred to as the father of sports medicine for his work caring for the gladiators of Rome [36]. Galen's teachings first described the spica pattern of application for bandages to the injured extremity. A famous French military surgeon, Ambroise Paré (1510–1590), heavily championed the teachings of Galen and those of another French physician, Guy de Chauliac. However, Paré is credited with applying the first hip spica cast [19, 35].

The hip spica is a type of full-body cast that includes the trunk and one or two legs. There are several different types of hip spica casts described in the literature. Traditional hip spica casts are by definition those that are either double-leg or one-and-a-half hip spicas. A one-and-a-half spica cast covers the entire leg down to the ankle on one side and then extends to above the knee in the other leg. When the cast covers both legs and the trunk it is called a double-leg hip spica. Most double-leg hip spicas are put on with the hips and knee both flexed 90°. The 90–90 designation is also used to describe a traditional hip spica cast. Double-leg hip spica casts have been applied routinely in the USA since first used in 1898 by Harvey Cushing [37].

If the hip spica covers only the leg from above the ankle to the trunk it is referred to as a single-leg hip spica. It is also called or referred to as a walking hip spica cast [38]. Early description of the use of single-leg hip spica casts for femoral fracture treatment can be found in a 1929 publication by Conwell [39]. The choice of hip spica cast applied depends on the surgeon and the pathology being treated with the cast. In addition to the common use of hip spicas for the treatment of femur fractures, they are also used in developmental dysplasia of the hip and other pathology affecting the hip joint.

There are other hip spica constructs worthy of mention. The first is a hybrid construct involving a traction pin placed in the distal femur, which is incorporated into a femoral cast brace. Traction can then be pulled through the brace. In a study of more than 70 patients using this technique, excellent results were reported in the children younger than 10 [40]. This hybrid method was not effective in the adolescent patient, which is consistent with previous studies investigating the traction with delayed casting model. A study from the Philippines by Gracila et al. reported results using a different type of hybrid technique, in which a distal tibial traction pin was incorporated into a hip spica cast [41]. The knee was in full extension for the traction, and the children stayed in the hospital an average of 5 days after the injury. The authors reported good results with 19 of 20 patients with a mean age of 7.2 years, healing in an acceptable position. They reported four minor complications, including two superficial pin-site infections, one sacral ulcer, and one patient with an allergy to the casting materials, which required removal of the cast. Younger ambulatory patients (less than 5 years old) may be placed in a walking-type spica, which allows for functional ambulation and improved caregiver satisfaction. Compared to traditional methods of spica application, this method has similar outcomes with respect to union time and fracture alignment [42].

The application of an immediate hip spica cast for an isolated femur fracture remains the standard of care for children aged 6 months to 5 years of age with less than 2 cm of shortening [43, 44]. A study from Switzerland followed 22 preschool children treated with immediate hip spica casting [45]. At 7.5 years of follow-up, only one patient had a leg length difference greater than 2.5 cm. One other patient had a mild rotational deformity and two more had a mild limp. Exceptions to application of immediate hip spica include significant thigh or leg swelling, shortening of more than 2 cm, and other associated injuries. The *telescope test,* described by Thompson et al., which can be performed in the operating room, has been described as a means to help to decide whether or not to continue with the immediate hip spica cast or to delay with skin or skeletal traction [46]. With the child relaxed, if more than 3 cm of shortening is evident with mild axial compression on lateral fluoroscopic images, then traction is employed instead of immediate spica casting. Using this maneuver, the authors reduced the number of children with shortening of greater than 2.5 cm from 18 to 5 %. However, clinical practice usually allows for immediate hip spica casting in almost all children less than 5 years of age, and the telescope test is not applied routinely by the majority of surgeons.

Technique Tips for Application of a Single-Leg Hip Spica Cast

Though spica casting may be performed at some institutions in the emergency room in selective instances, we perform all of our hip spica cast applications in the operating room. Prior to bringing the child to the operating room, adequate supplies are confirmed (Table 7.2). The patient is taken into the operating room suite and anesthesia or sedation is given. For comfort and to avoid skin irritation from the yardstick, we cover the yardstick with the pink leukoplast tape. We also sprinkle baby powder on the yardstick to minimize skin irritation. The 6″ stockinette for the torso is measured from the nipples to below the groin and then placed on the child. Depending on the size of the fractured leg, we use 2″ or 3″ stockinette for the leg measured from just above the hip to heel. We then place the child on the hip spica box (Fig. 7.7) and move the box with the child to the end of the operating room table. The yardstick is positioned to be underneath the stockinette against the child's back. The child is adjusted on the hip spica box so that there is access to the scapulae. You should be able to wrap silence cloth easily around the level of the nipples (Fig. 7.8). Adjust the child on the spica box so their perineum is securely against the post. At this point, place the rolled-up ABD pads underneath the stockinette flush against the chest to allow room for expansion of the lungs and abdomen. We recommend the use of a few assistants to make application a smooth process. One person should be at the head by the anesthesiologist, and another person holds the arms up over

Table 7.2 Recommended supplies for application of a hip spica

Recommended supplies to have available for application of a hip spica
• Hip spica box
• Stockinette for trunk and leg (s) 6″ width (torso) measured from below groin to above the clavicle. The 2″ width for the single leg is measured from the heel to the hip
• Folded over two ABD pads that are rolled up and placed under torso stockinette to allow for stomach and chest expansion
• Cast padding soft roll 3″, 4–5 rolls total
• Silence cloth 3″ width to apply around the chest at proximal edge and around the ankle to prevent pressure ulcers
• Fiberglass 2″, 6–8 rolls total
• Cast saw
• Good pair of scissors
• Elastoplast tape -2″ width (secure padding and cast around the belly hole)
• Leukoplast tape -2″ or 3″ pink water-resistant tape to pedal groin area of the cast
• Baby powder
• Water bucket (preferably warm)
• C-arm

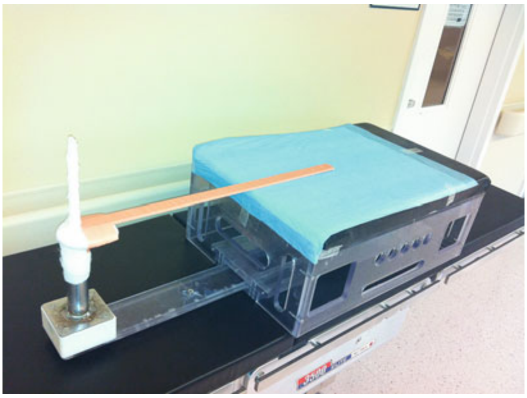

Fig. 7.7 A hip spica box

the child's head. Another person is holding the non-fractured leg and the final assistant focuses on pulling traction and positioning the injured leg. The surgeon should roll the cast and apply the mold.

When everyone is ready, the silence cloth is then wrapped around the nipples and down at the ankle, above the malleoli (Fig. 7.9). We incorporate the silence cloth in these locations to minimize the development of pressure sores from casting. We then start wrapping the soft roll cast padding. We prefer to use 3″ rolls. Maintain tension and compression as this is applied. We try to obtain 50 % overlap. Extra time is spent around the hips, wrapping in the spica pattern described originally by Galen. Make sure that there are

Fig. 7.8 Placement of silence cloth around chest

Fig. 7.9 Continue wrap of silence cloth down to ankle

Fig. 7.10 Soft roll cast padding is wrapped down the fractured leg

three to four layers around the hip area. The soft roll is then taken down the fractured leg (Fig. 7.10).

While flat-plate radiographs may be routinely utilized at many institutions, and may represent a more cost-effective option, particularly for stable fractures, C-arm fluoroscopy may have particular value for unstable fractures requiring immediate feedback regarding the optimal reduction, and is preferred at our institution. The C-arm should be brought in perpendicular to the fractured femur to make it easier to obtain lateral images. Evaluate with fluoroscopy the fracture, how much shortening is present, and then how much effort is required to maintain the reduction. If considerable traction on the leg with appropriate valgus mold is required, we will then roll a very short long-leg cast component first and allow this to harden. This will allow an assistant to distract the distal fragment to help with alignment of the fracture without putting indents in the popliteal fossa from pressure holding the reduction. The knee is flexed to between 45° and 60° in the short long-leg cast. If the fracture needs minimal molding or distraction, we will roll the torso and waist component of the hip spica cast first and then incorporate the leg as the last part. Because diaphyseal femur fractures tend to drift into varus and procurvatum, it is important to place a valgus mold with pressure anteriorly while the cast is being applied. Also, during molding the position of the hip needs to be considered. For midshaft fracture patterns, we position the hip in 30° of flexion, 30° of abduction, and 20° of external rotation. For more proximal subtrochanteric variants the amount of hip flexion needs to be increased to 45–50°. Similarly, for more distal supracondylar region femoral shaft fractures, adjustments need to be made in positioning. We place the hip in 20° of flexion, 20° of abduction, and 10–15° of external rotation. However, the optimal position of hip and knee flexion of the spica cast in children is variable and often institutional in nature. Placement of children in the 90–90 sitting position provides greater ease of care for placement in strollers and car seats and remains a common practice.

Extra time needs to be spent wrapping the cast to attach the leg component to the torso. A figure-8 pattern should reinforce this vulnerable area of the single-leg spica. We will also use extra fiberglass slabs across the hip joint to make this junction even stronger. If not done properly, a triangular area sometimes referred to as “resident’s corner” can develop in the posterior part of the hip spica by the posterior superior iliac spine. On the contralateral hip make sure that none of the cast extends far below the anterior superior iliac spine. This incorrect casting technique can cause impingement or irritation of this leg with flexion. Once the cast has been rolled and the appropriate mold placed, it is time to preen and pedal the cast. We first mark out a belly hole to cut out with a sagittal saw. This allows for easy breathing and for the patient’s stomach to expand with meals. Once the square area is removed from the center of the torso, the area is prepared using tape in a sunshine pattern. We then pedal the groin, buttock, and upper torso area with the leukoplast 2″ and 3″ tape. Final fluoroscopic shots need to be taken to confirm reduction and mold of the cast. Once the cast has been prepared, the patient can then be weaned off sedation and transferred to the recovery room.

We routinely keep children in the hospital after hip spica for 24 h to monitor for any issues related to the cast, such as peroneal nerve palsy or compartment syndrome. Make sure that double diapers are placed after completion of the hip spica cast, as it is not uncommon for the patient to soil themselves immediately upon waking up from anesthesia.

Other Modifications to This Technique

- Some authors strongly advocate the use of Goretex liners instead of the stockinette and cast padding [47]. This is referred to as a Pantaloon cast. This can decrease skin problems. We have found that excellent results can be obtained with the Elastoplast tape and leukoplast tape to minimize skin irritation.
- The cast can be rolled to include the contralateral thigh to make it a 1.5 hip spica cast if desired by the physician.
- If a 1.5 hip spica cast is rolled, consider use of a connecting bar which can minimize the chance for mechanical failure of the cast and provide a convenient way to transport and move the patient.

Duration of treatment in the hip spica in weeks is determined by the general formula of 3+ the patients' age. For example, a 5-year-old would be expected to be in the hip spica for 8 weeks of treatment.

Complications of Hip Spica Application

Application of a hip spica cast is not a benign event, and serious complications have been reported from its use. The complication rate associated with both traditional and single-leg hip spica casting has been reported to be between 5 and 45 % [30, 42, 48, 49]. One of the more problematic and often neglected complications of hip spica application for femur fractures involves skin breakdown. In a study from Boston Children's Hospital, 300 hip spica casts in 297 patients were followed from 2003 to 2009, and 77 (28 %) developed skin complications [50]. Almost one-third of these patients required a second trip to the operating room for a cast change. The authors identified risk factors for skin complications with spica casting that included cast use for more than 40 days, victims of child abuse, and younger age. Casting is often thought of as a safe procedure, but this study highlights the importance of applying a well-padded cast in the treatment of femur fractures in the 6-month to 5-year age group.

The same study of complications at Boston Children's also identified a high percentage of casts that needed wedging as part of the treatment (44 out of 300 = 14.7 %) [50]. This is slightly higher than some other series on cast treatment for femur fractures including Sugi and Cole (4 %), Epps et al. (7 %) [38], and Martinez et al. (8 %) [51]. However, the study with the highest rate of cast wedging was the study by Flynn et al. comparing traditional hip spica to single-leg hip spica casts. The authors found that 25 % of children in the single-leg group required wedging during follow-up treatment [42]. These numbers all highlight the importance of close weekly follow-up with scrutiny of lateral radiographs to make sure that the cast is maintaining an acceptable fracture position (see Table 7.3). It should be mentioned that a potential complication of cast wedging can be development of a peroneal nerve palsy, especially for casts placed in the 90–90 position. In a study from Johns Hopkins, 4 patients out of 110 had 90–90 casts placed and underwent a wedging of the cast for correction [52]. Fortunately, all four palsies resolved with removal of the cast. If there is concern about the amount of correction needed with a wedge, reapplication of a new cast or a period of traction before reapplication of the cast can be considered.

The effect of caring for a child in a hip spica cast should also be considered. In a study by Hughes et al., they examined the impact on children and their caretakers of a spica cast placed on children aged 2–10 years [53]. In families with two working parents, 3 weeks away from work was required to care for the child. Mobility was reported as the primary problem in the care of the child. This study also emphasized that caring for younger preschool children was easier than for the school-aged children. The difficulty in caring for, transporting, and keeping school-aged chil-

Table 7.3 Acceptable deformity by patient age for diaphyseal femur fractures

Age	Varus/valgus	Anterior/posterior	Shortening in cm
Birth to 2 years	30	30	15
2–5 years	15	20	20
6–10 years	10	15	15
11 to skeletal maturity	5	10	10

With permission from Kasser JR, Beaty JH. Femoral Shaft Fractures. In: Rockwood & Wilkins Fractures in Children. 6th ed. Philadelphia: Lippincott Williams & Wilkins; 2006

dren clean are all problems that have driven many surgeons to recommend operative fixation for school-aged children (between ages 6 and 11).

Cast breakage was reported at 11 % by Epps et al. in their study looking at application of single-leg hip spica cast. In a study comparing the single-leg to traditional hip spicas, Flynn et al. reported a 0 % cast breakage rate in their single-leg arm of the study. The authors commented that the improvement in breakage rate was because they incorporated suggestions from the Epps study to make the cast more sturdy with the use of anterior cast strut reinforcement [42].

Large and Frick reported on two cases of compartment syndrome that developed after application of an immediate hip spica cast [54]. The position of these casts was 90–90, and because the involved leg was cast to the toes, diagnosis post-cast was very challenging. Because of this, the authors reported making changes to their casting technique that bear mentioning. First, the foot is not incorporated into the cast; it stops above the malleoli (as we describe in our preferred technique). This allows for good access for neurovascular checks and swelling of the limb. They also now roll the “short” long-leg component of the cast holding the limb by the heel and not the calf. On review, they attributed pressure to the posterior calf during cast molding and traction may have played a contributing role. They also recommend a very low threshold on follow-up examination to completely remove the cast for feelings of tightness, pain, or any neurologic dysfunction.

Nonunion is very rare in the pediatric population with a midshaft femur fracture. Workup should be directed to exclude causes for the nonunion including infection and possible metabolic bone disease.

Concluding Remarks

Traction and casting for the treatment of femur fractures in children have been utilized for many centuries and can be traced back to the teachings of Hippocrates. Spica bandages were attributed to the famous physician Claudius of Galen, and the first spica cast to the French surgeon Ambroise Paré. While there has certainly been a shift in emphasis in orthopedics on operative intervention, the art of casting and the use of traction continue to have an important place in the armamentarium of today’s pediatric orthopedic surgeon.

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8

Treatment of Pediatric Diaphyseal Femur Fractures: External Fixation

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Introduction

External fixation is an efficient method to align and stabilize diaphyseal femoral fractures. Although it is primarily used for temporary fixation, selective indications continue to exist for external fixation in the current treatment armamentarium. This chapter provides a historical perspective on external fixation for diaphyseal femoral fractures, reviews modern selective indications, provides management principles, and concludes with outcomes and complications of this technique.

Historical Perspective

The concept of external fixation was developed in the late 1800s. Its use in children was first described in 1929 [1] with modern devices being developed by Wagner in 1971 [2]. Since then, this technique has alternated between periods of great enthusiasm and intervals of total disrepute [3]. In the 1970s and 1980s external fixation gained popularity in the treatment of pediatric femoral fractures over traction or cast immobilization [4–6]. The primary advantages of this technique included rapid stabilization without the need to expose the fracture site, and the ability to allow early weight bearing and range of motion [7]. Enthusiasm for this technique waned, however, as a number of complications were reported, including pin track infections and loosening, delayed union or malunion, leg length discrepancy, heterotopic ossification, refracture, and hypertrophic scar formation [8–10].

Tolo [10] first reported on a series of 14 patients between 3 and 15 years of age who were treated with the Hoffmann device from 1978 to 1981. The indications for use of an external fixator were open fractures with skin loss in a majority of the patients (71 %), inadequate fracture reduction by manipulation and casting in three patients, and closed fracture requiring a fasciotomy in one patient. Fracture union was present at a median of 17 weeks. No patient developed osteomyelitis and all patients regained full joint motion. However, three refractures occurred after apparent union, three patients had leg length discrepancies of 2 cm or more, and one patient had a residual angular deformity after fracture healing. Other series by Alonso et al. [11] and Aronson et al. [12] reported similar outcomes and complications with primary external fixation and early weight bearing.

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In the 1990s there was a transition away from primary external fixation as flexible nails gained popularity. In a prospective randomized study, Bar-on et al. [13] compared ten fractures treated with external fixation to ten fractures treated with flexible intramedullary nailing. They reported that the early postoperative course was similar; however the elastic nail group recovered faster with an earlier time to full weight bearing, time to full knee range of motion, and return to school. Complications in the external fixator group included two deep pin tract infections, one refracture, and one delayed union. In the flexible nail group, one patient developed a foot drop caused by operative traction, two developed bursitis over the medial nail insertion site, and one required early removal due to proximal nail migration. In conclusion, they recommended the use of flexible intramedullary nails and reserved external fixator use for open or severely comminuted fractures.

More recently, some authors have tried to revitalize interest in using external fixators for primary stabilization in femoral shaft fractures. Hedin et al. [14] proposed that many of the complications from external fixator use were due to technical errors such as poor screw fixation, premature fixator removal, or malreduction. In a series of 97 consecutive femoral fractures, they demonstrated fracture union in an average of 61 days [15]. Two patients had residual varus angulation of more than 10°, and seven patients had a residual procurvatum of more than 15°. Two patients developed refracture and one developed heterotopic ossification. Although 36 patients developed pin-site infections, all of these resolved with local wound care or oral antibiotics, and no patient developed a deep infection or pin loosening.

Modern Selective Indications

Currently the primary indication for external fixation of diaphyseal femoral fractures is in the setting of severe soft-tissue injury (i.e., open fractures, contaminated wounds, burns) especially with neurologic or vascular compromise (Fig. 8.1a–f). External fixators can either be used temporarily or definitively to align and stabilize the limb while the soft-tissue envelope is serially debrided and the neurovascular structures are repaired. It is important to have a preoperative plan for pin placement that avoids contamination of future surgical approaches to address the fracture, or donor sites for future soft-tissue transplantation procedures.

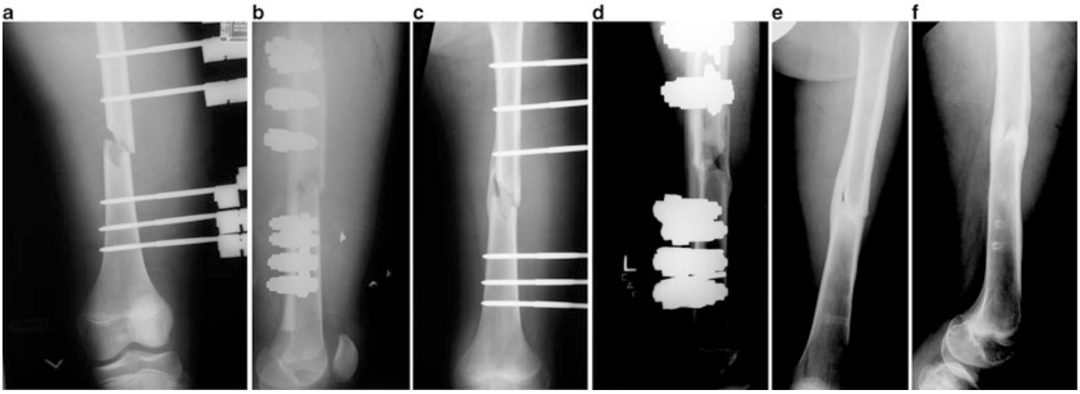

Fig. 8.1 (**a**–**f**) 14-year-old male who sustained a 30-ft fall into a pond. He presented with a grade 2 open left diaphyseal femur fracture with gross contamination of the wound. AP (**a**) and lateral (**b**) radiographs after urgent irrigation and debridement and application of an external fixator demonstrate acceptable alignment with slight distraction at the fracture site. He underwent two more serial debridements over the next 5 days and his wound was closed over a drain. At 3 months post-op, AP (**c**) and lateral (**d**) radiographs demonstrate significant callus formation with acceptable alignment. The external fixator was taken off after 5 months. AP (**e**) and lateral (**f**) radiographs at his 6-month post-op visit demonstrate a well-healed fracture

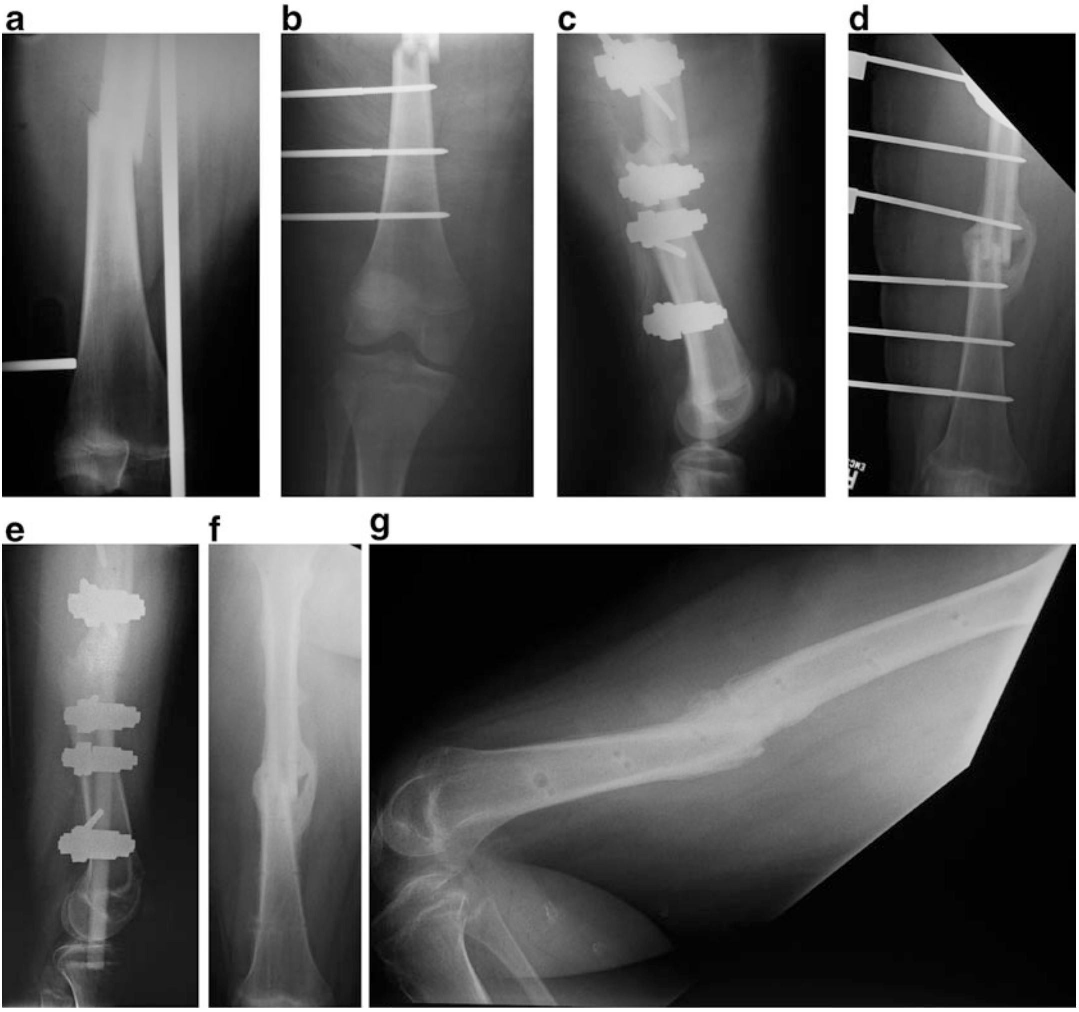

Fig. 8.2 (**a**–**g**) 14-year-old male who was involved in a bicycle versus automobile accident. He sustained a subdural hematoma, right clavicle fracture, right wrist fracture-dislocation, and right femur fracture. AP (**a**) radiograph demonstrates a right grade 1 open femur fracture. This was treated with urgent irrigation and debridement and primary wound closure. AP (**b**) and lateral (**c**) postoperative radiographs demonstrate external fixator application. At 3 months post-op AP (**d**) and lateral (**e**) radiographs demonstrate appropriate callus formation and remodeling of the fracture. At 5 months post-op AP (**f**) and lateral (**g**) radiographs demonstrate fracture healing after removal of the external fixator

Patients with significant closed head injuries or multiple extremity injuries may also benefit from early fracture stabilization with an external fixator (Fig. 8.2a–g) [16]. The concept of damage control orthopedics was introduced by Pape et al. [17] who demonstrated decreased morbidity and mortality in adult patients with severe multisystem injuries who underwent early temporary fracture stabilization using external fixators. This staged approach was thought to allow for appropriate resuscitation of a physiologically unstable patient prior to exposing them to the "second hit" of the surgical intervention. Although this concept remains controversial in the pediatric population, the additional advantage of early external fixation is that it stabilizes the limb during transportation of the polytrauma pediatric patient to tertiary referral centers.

Extremely proximal or distal femoral fractures may also benefit from external fixation as compared to intramedullary stabilization or plating, as it can be difficult to obtain adequate fracture stability while avoiding physeal injury in these patients (Fig. 8.3a–h). In the rare instance, an epiphyseal pin can be used if the fracture extends close to the physis. It is important to remember that this pin is intra-articular, and should be removed expeditiously to avoid joint sepsis. Patients with benign pathologic fractures at the distal meta-diaphyseal junction are also good candidates for external fixation, as alternate fixation strategies may not provide adequate stability (Fig. 8.4a–f).

External fixators can also be used in revision cases to treat traumatic malunions. Especially in patients with residual three-dimensional deformities, a circular external fixator can be used to correct the deformity over time (Fig. 8.5a–h).

Management Principles/Technical Tips

After determining that an external fixator is the optimal treatment for the child with a femur fracture, our preferred technique is a unilateral fixator that is left in place until union is achieved. For stable fracture patterns this is quite successful. Fracture alignment optimization is achieved by periodic radiographic evaluation and shifting of the external fixator, if necessary, to improve upon alignment during the treatment period. For unstable fracture patterns, treatment should follow the same principle, and the end-point of complete union is mandatory to prevent the risk of refracture (Fig. 8.6a–h).

Technical tips to the placement of external fixation pins in a child revolve primarily around limiting injury to the growth plate. Because of

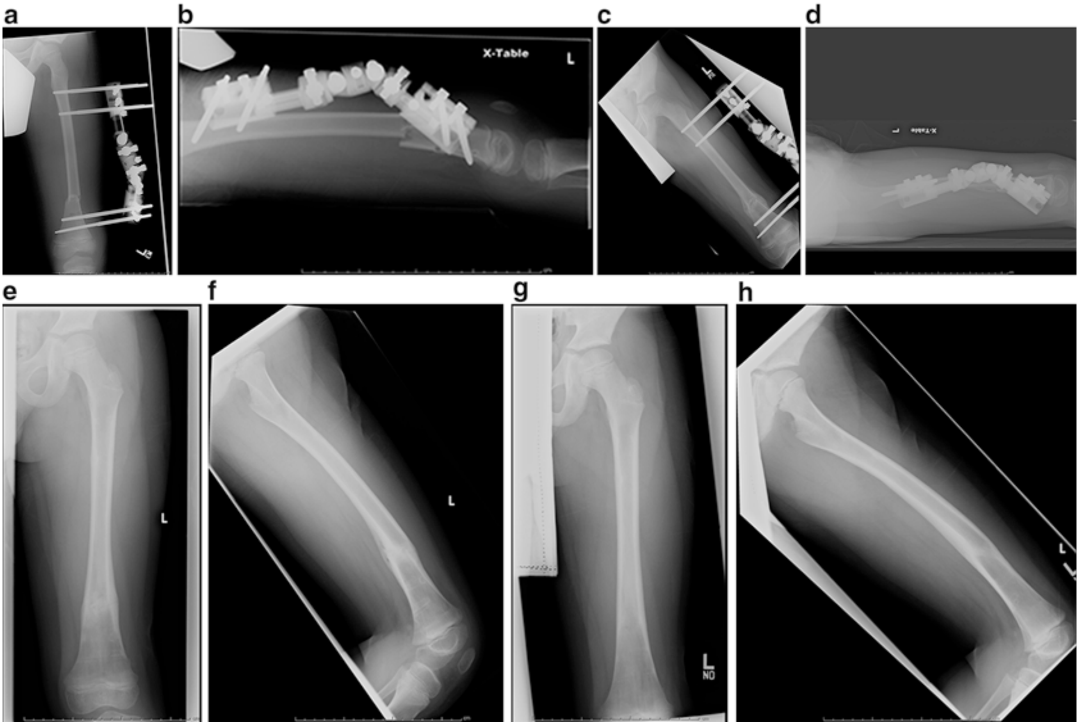

Fig. 8.3 (**a**–**h**) 7-year-old male who sustained a left distal third diaphyseal femur fracture after a jet ski accident. He was treated at an outside hospital and transferred to our facility. AP (**a**) and lateral (**b**) radiographs after external fixator application. AP (**c**) and lateral (**d**) radiographs at 3 months post-op and at 4 months post-op (**e**, **f**) after the external fixator was removed. 1-year follow-up radiographs (**g**, **h**) demonstrate near-complete remodeling of the fracture

Fig. 8.4 (**a**–**f**) 14-year-old male who sustained a left pathologic supracondylar femur fracture through a suspected unicameral bone cyst. AP (**a**) and lateral (**b**) preoperative radiographs demonstrate significant deformity with a juxtaphyseal fracture. AP (**c**) and lateral (**d**) postoperative radiographs demonstrate appropriate alignment. An epiphyseal pin was used in external fixator construct. The fixator was removed at 3 months post-op. AP (**e**) and lateral (**f**) 11-month postoperative radiographs demonstrate appropriate fracture healing with a small residual cyst

the potential risk of thermal injury, placement of pins should be at least 1–2 cm from the physis to reduce thermal injury and potential infection risk from a pin tract infection. Moreover, the pins should be placed parallel to the physis to aid in the reduction of the fracture, and they definitely should be placed parallel to each other. Otherwise, the principles for external fixation in adults should be applied to children: optimizing pin placement with near-near and far-far positions, placement through intact uninjured skin if possible, and semicircular design, if needed.

Perhaps just as important to the application of an external fixation device is post-application pin care. Utilization of either manufactured foam spacers or surgeon-fabricated spacers to maintain tension at the skin will reduce pin-site complications and skin irritation. Furthermore, educating the family regarding daily pin-site care will reduce complications, as well.

Often the choice of using the external fixator is based on the speed by which fixation can be achieved in these patients (vascular compromise, multi-trauma, or burns) and therefore your

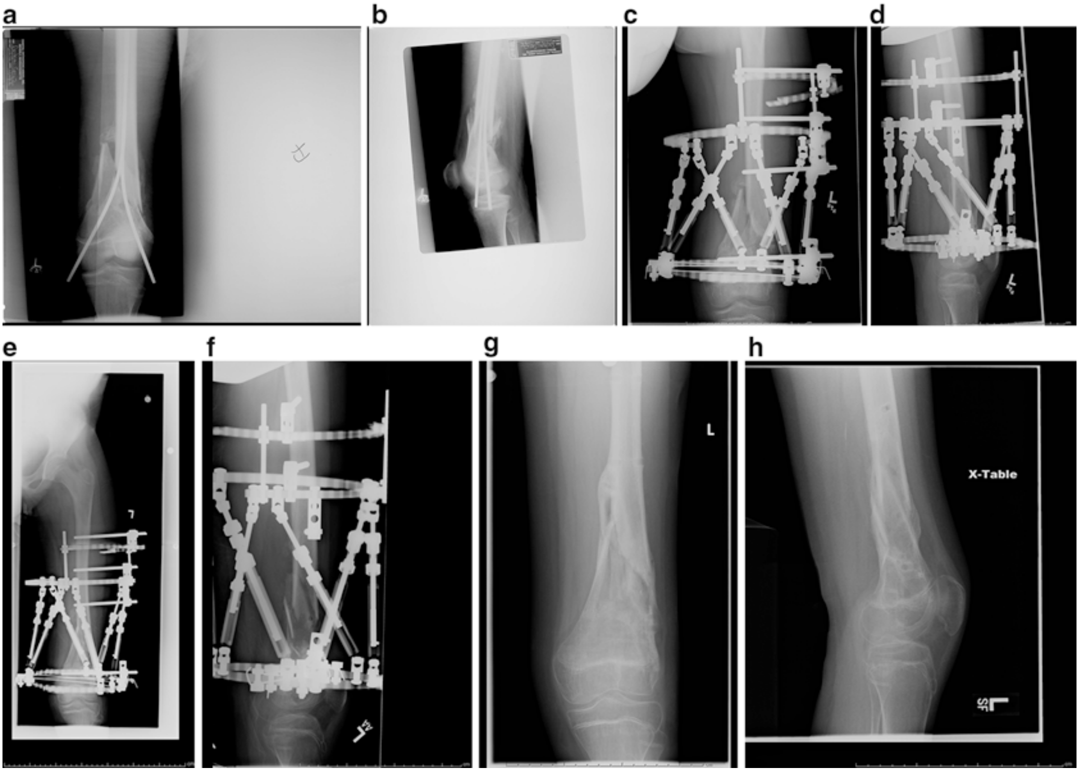

Fig. 8.5 (**a**–**h**) 15-year-old male who was involved in a motor vehicle accident. He sustained a long oblique left femur fracture and was treated at an outside facility with titanium elastic nails. AP (**a**) and lateral (**b**) radiographs at 4 weeks post-op demonstrate a malaligned fracture with 3 cm of shortening and medial translation of the distal fragment. AP (**c**) and lateral (**d**) postoperative radiographs after fracture revision with circular external fixator application. AP (**e**) and lateral (**f**) radiographs at 2 months post-op demonstrate improved alignment. The external fixator was removed at 4 months post-op. AP (**g**) and lateral (**h**) radiographs at 6 months post-op demonstrate a healed fracture with acceptable alignment

treatment algorithm is limited. However, the outcomes of external fixation can potentially be augmented by using concomitant intramedullary fixation, especially if the choice of external fixation is made because of fracture location and pattern. The placement of elastic intramedullary nails at the time of surgery, in isolation, may not control a comminuted or metaphyseal fracture successfully; but, concomitant placement of an external fixator for a short duration may allow initial fracture healing with good alignment. The external fixator can then be removed early to reduce the risk of infection and skin complications, without the risk of refracture or loss of reduction because of the already placed intramedullary fixation. The indications for this technique are limited, however, especially with newer metaphyseal plate technology for older children.

Regardless of whether you utilize a pure external fixation technique or the hybrid method, there are a few bone-healing principles that need to be addressed. Whereas external fixation may inherently allow for some micromotion at the fracture site, it is important to advance the patients' axial dynamization via progressive weight bearing to promote callus formation and stability. This should reduce the amount of time needed in the external fixator and decrease the risk of refracture once removed. Furthermore, if the external fixator cannot achieve a perfect reduction, or if there is significant injury at the fracture site, then gap healing

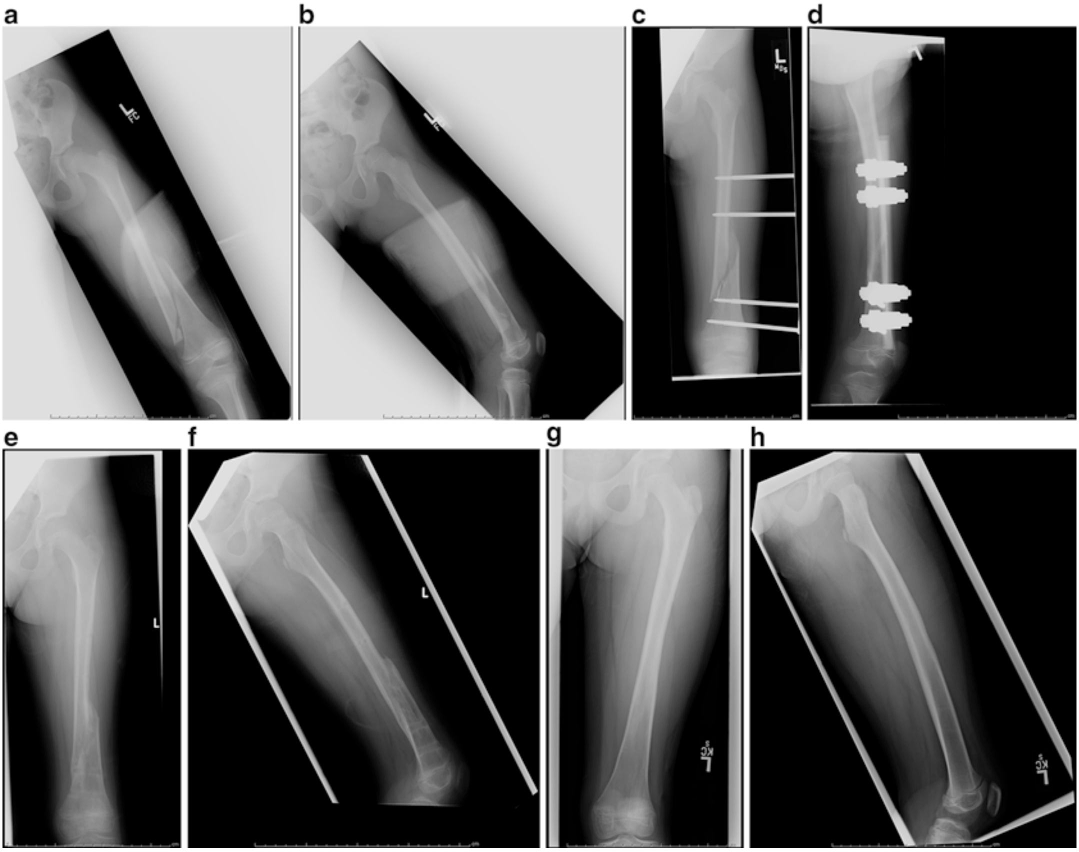

Fig. 8.6 (**a**–**h**) 6-year-old female who presented to the emergency department after a fall from a slide. AP (**a**) and lateral (**b**) radiographs demonstrate a left closed long oblique distal third diaphyseal femur fracture. An external fixator was used to stabilize the fracture (**c**, **d**) as it was thought to be length unstable and too distal to treat with a submuscular plate. The external fixator was removed at 3 months post-op (**e**, **f**). AP (**g**) and lateral (**h**) 11-month postoperative radiographs demonstrate fracture healing and appropriate remodeling

may be important and gradual modification of the fixator frame could salvage a potential risk of delayed or nonunion.

Outcomes and Complications

Reported outcomes for external fixation of femur fractures are generally good. Blasier and colleagues utilized an external fixator in children (mean age 9 years) for a duration of just under 3 months with progressive weight bearing with no nonunion and good outcomes [18]. These authors only had a refracture rate of 1.4 %. Yet, Evanoff and colleagues reported on alignment issues and determined that 84 % remained fixed in good alignment, but the remaining had some loss of reduction (but less than 5°) [19].

Gregory et al. discussed the overall complication rate of children in an external fixator and found that 107 % had some issue with the treatment [9]. Most of these were minor complications including psychosocial issues with dislike of the pin-site scars and unwillingness to attend school with the fixator in place. However, 30 % of the children in this study demonstrated major complications that included delayed union, post-care fracture, and infection (Fig. 8.7a–g).

The most common complication is pin tract infection, which occurs in approximately 50 % of the cases. But this complication is usually minor, since it can be easily cared for with pin-site care

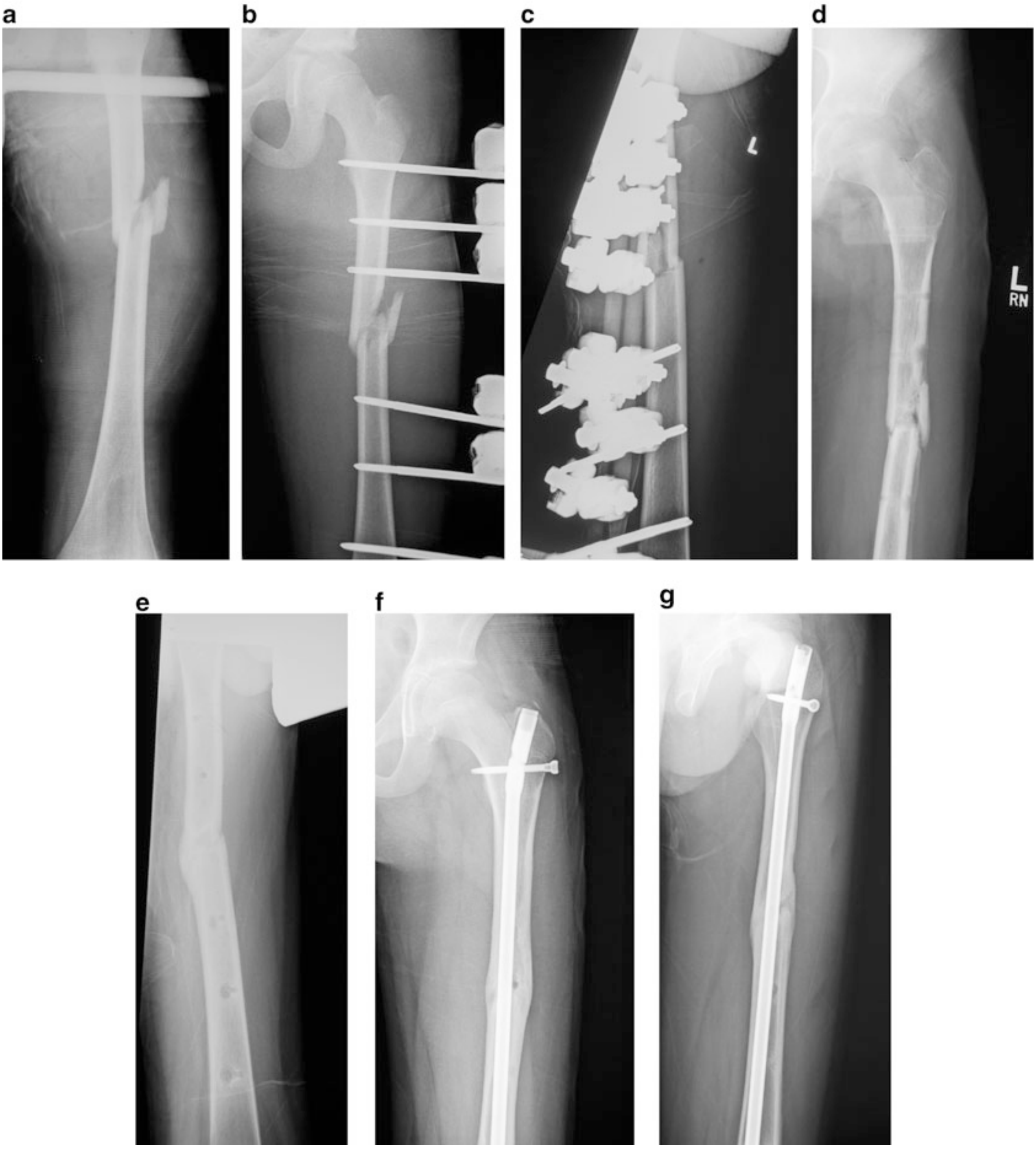

Fig. 8.7 (**a**–**g**) 13-year-old male who sustained a grade 2 open left diaphyseal femur fracture (**a**) after a motocross accident. AP (**b**) and lateral (**c**) radiographs after irrigation and debridement and application of an external fixator. The fixator was dynamized at 3 months post-op due to delayed union. An infection was excluded (**d**, **e**) and the external fixator was revised to an intramedullary nail at 6 months post-op. AP (**f**) and lateral (**g**) radiographs 8 months from the injury demonstrate a well-healed fracture

and antibiotics. Refracture rate is also reportedly higher than other treatment modalities with an incidence as high as 21 % (but as low as 1.5 %) [10, 12, 18, 20]. This higher rate is most often associated with the specific pattern of short oblique fractures, and therefore should be somewhat preventable with appropriate management. The surgeon should either consider prolonged use of the fixator until complete union is achieved or possibly consider initial treatment with a hybrid fixation technique that utilizes intramedullary implants and an external fixator which can be removed early after early osseous healing. Multiple authors have written on refracture rates, and most attribute the increased risk to the amount of fracture healing at the time of fixator removal, prolonged rigidity of the limb due to fixator use, and operative technique [7, 12, 15].

Less commonly, malunion is possible with external fixation because the fracture is often reduced in emergency settings. During these situations sagittal and coronal alignment is often achieved because they are easily assessed by orthogonal fluoroscopy views, but axial rotation is sometimes underassessed and the femur can be left in slight external rotation. On this issue, Sola et al. found that auxiliary pins could be placed to increase stability of fixation and decrease the risk of reduction loss [21]. Other, less common complications include physeal injuries from pin placement, de novo fractures through pin sites after pin removal (especially when bigger pin diameters are used on smaller children), and vascular injury during pin placement.

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9

Treatment of Diaphyseal Pediatric Femur Fractures with Flexible Intramedullary Fixation

Karl Rathjen and Phillip L. Wilson

Introduction

Femur fractures are the most common pediatric injury requiring hospitalization [1]. As with other diaphyseal fractures, improved knowledge of the biology of fracture healing, as well as advances in fixation methods and operative techniques, has resulted in increased rates of operative stabilization of femoral shaft fractures in children. Surgical stabilization may allow early mobilization, thereby reducing the care burden on families and decreasing hospital stays. Flexible intramedullary nail (flexible IMN) fixation has been used effectively for pediatric diaphyseal femoral fracture fixation [2–15]. Additionally, flexible IMNs provide the benefits of intramedullary fixation without the risk of vascular or articular injury. Antegrade use of flexible IMN from the proximal lateral cortex avoids the piriformis fossa and the greater trochanter, thereby eliminating the possibility of vascular injury and avascular necrosis of the femoral head, as well as growth arrest at the greater trochanter. Unlike retrograde rigid nails, retrograde flexible IMN may be introduced through the metaphysis, thereby avoiding dissection into the knee joint or violation of the distal femoral physis.

Indications

Indications for flexible IMN of pediatric diaphyseal femur fractures are influenced by patient and fracture characteristics. These have been examined in clinical series and biomechanical studies, and recommendations have been addressed by organizational review. As part of the American Academy of Orthopaedic Surgeons (AAOS) clinical practice guideline (CPG) development initiative, guidelines on the management of pediatric diaphyseal femoral fractures were published in 2009 [16]. Flexible IM nailing is noted as an option with moderate evidence (Level of Evidence: III; Grade of Recommendation: C) for the treatment of children aged 5–11 years.

Children younger than 5 years may better tolerate spica casting due to faster time to union, decreased risk of unacceptable shortening, and smaller body size, allowing reasonable parental cast care and transfers. In the 5- to 11-year age group, flexible nailing may be preferred over spica casting and external fixation due to decreased times to weight bearing and return to activity [17–19]. Other acceptable treatment

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options, such as compression plate fixation, submuscular bridge plating, or rigid nailing, may have certain indications, advantages, or disadvantages relative to flexible IMN, but have yet to be rigorously studied in comparative fashion in this age group. Patients younger than 5 or older than 11 may also be well served by flexible IM nailing, but may only be applicable when features such as fracture pattern, weight, comorbidities, or caregiver issues favor this type of intramedullary fixation [20–23]. Fracture pattern and patient weight are among the most clearly recognized factors that influence the ability to control femoral diaphyseal fractures with flexible IMN, and will be further detailed below. Knowledge regarding implant properties and biomechanics will assist in the proper patient selection and technique for flexible IMN use.

Radiographic Assessment

Standard AP and lateral radiographs of the femur, which include the hip and the knee joint, are required for accurate preoperative assessment and surgical planning related to flexible IMN use. Diaphyseal fractures may be associated with femoral neck fractures, intertrochanteric fractures, or hip dislocations and may be missed in up to a third of cases [45–48]. Transport and traction splints may obscure bony anatomy, and therefore multiple views may be required in order to adequately visualize the extremity. In some cases, the splint may need to be removed to optimize imaging. Fracture pattern, comminution, and degree of displacement and shortening should be taken into consideration when planning for implant choice, insertion technique, intraoperative reduction technique, and postoperative management.

Fracture Pattern

When considering femur fracture stabilization, length stability of the fracture is an important determinate for selection of flexible IMN. Transverse fracture patterns, or short oblique patterns with minimal comminution, are most length-stable and therefore most highly amenable to flexible IMN, without the risk of significant shortening. Long spiral patterns and comminuted fragments present risks of shortening over flexible IMN [24, 25]. For length-unstable patterns, other methods of fixation may be preferable to prevent the risk of unacceptable leg-length inequality at union. Alternatively, flexible IMN may be used in combination with supplemental single-leg spica fixation in selected cases [3]. Additionally, stainless steel Enders rods may be utilized and provide some benefit of additional stability or rigidity over titanium IMN fixation in carefully selected patterns [26]. Furthermore, use of Enders rod with a locking screw technique through the nail eyelet represents a viable option that extends flexible IMN use in potentially length-unstable patterns [27]. With this technique, the benefits of IMN fixation may be gained while decreasing the risk of shortening in these fracture patterns (Fig. 9.1a–c).

Implant Properties and Biomechanics

Familiarity with implant properties and fracture biomechanics will aid the surgeon during implant and technique selection when treating femoral diaphyseal fractures with flexible IMN. Steel and titanium differ significantly in stiffness properties, with a modulus of elasticity of 200 and 110 GPa, respectively [28–30]. In sawbones biomechanical modeling, titanium IMNs demonstrate some improved stability in torsion and axial compression over stainless IMN [29, 31]. Additionally, in these models, stainless nails demonstrated apparent increased slippage within distal femoral entry sites when compared with titanium implants [32]. It has been postulated that the flexibility of titanium nails may allow increased surface contact within the canal leading to decreased slippage in axial loading [31]. However, in clinical reports, several authors have reported good clinical outcomes with stainless steel nails in series including unstable fracture patterns [23, 33]. In these reports, steel nails were used with low rates of shortening and peri-implant complications when compared with titanium IMN series. Current bio-

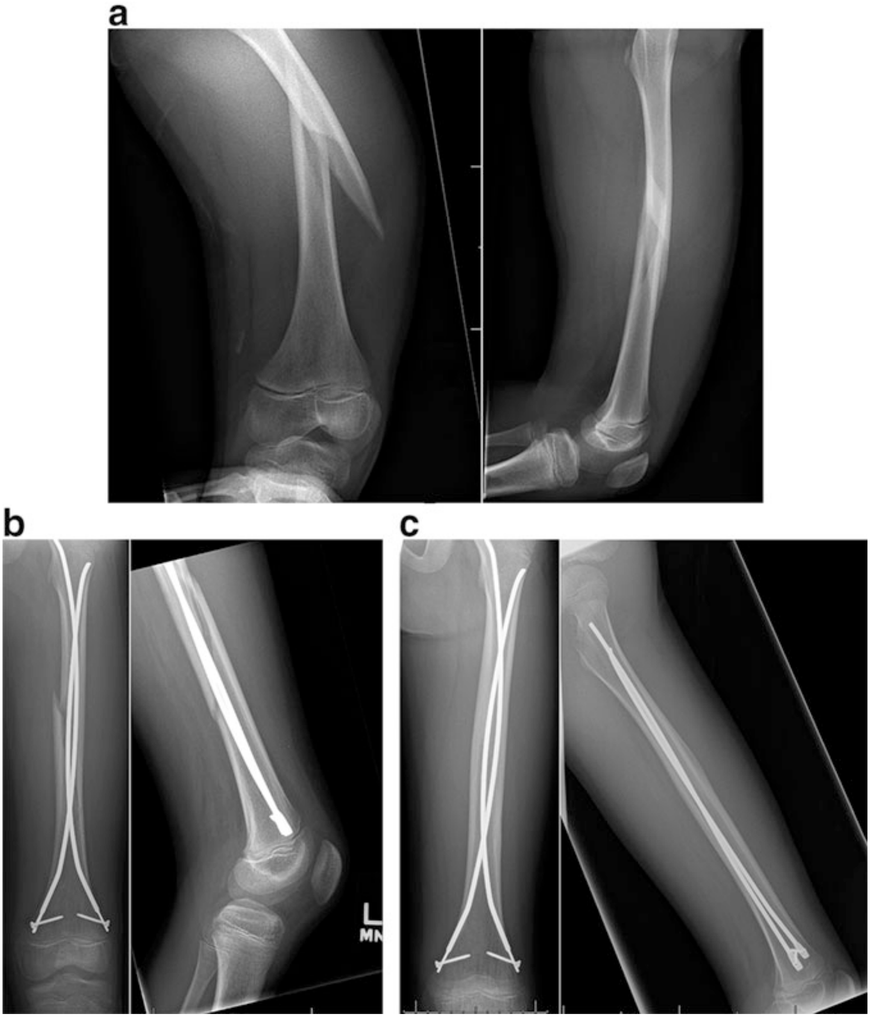

Fig. 9.1 (**a**) AP and lateral injury radiographs of 9-year-old with length-unstable diaphyseal femur fracture. (**b**) AP and lateral radiographs of stabilization utilizing stainless steel nails with a 2.7 mm "locking" screw in the insertion eyelet. (**c**) AP and lateral radiographs at 8 months post-stabilization

mechanical and clinical data may support the use of either steel or titanium IMN. Thus, diaphyseal fractures may be managed successfully with either implant when other technical and patient selection criteria are considered.

Nail Dimensions

Implant diameter is another important consideration affecting the stability of flexible IMN of diaphyseal femur fractures. While various patterns and numbers of nail configurations have been reported, balanced two-nail constructs have been shown to be most biomechanically stable. A combined diameter for the two nails of >80 % of the narrowest canal diameter measurement has been recommended for maximal stability to prevent shortening and angular deformity [34, 35]. Conversely, increasing diameter significantly beyond 40 % of canal diameter per implant may increase the risk of loss of anterior femoral bow and rotational malalignment [36].

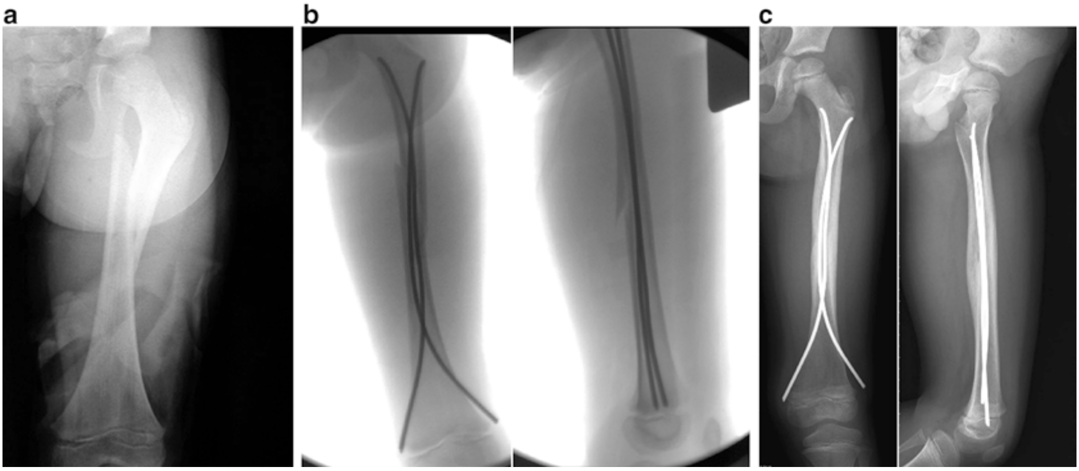

Fig. 9.2 (**a**) Injury radiograph of 6-year-old with isolated femoral shaft fracture. (**b**) AP and lateral radiographs of stabilization with flexible titanium nails placed with retrograde technique. (**c**) AP and lateral radiographs of healing 6 months following nail insertion

Patient Weight Considerations

Patient weight has been demonstrated as an important factor affecting outcomes of pediatric diaphyseal femur fractures managed with flexible IMN. Increased rates of malunion and implant complications have been reported in flexible IMN fixation in patients >49 kg [35, 37]. Angular deformity, shortening, and backing out of implants with axial loading have been reported in this heavier population, as well as patient age >11 years [6, 38, 39]. Biomechanical testing has shown deformity of titanium nail constructs when loads exceed 600 N [40]. Steel constructs may resist deformity to a greater degree in the clinical setting and may be considered for heavier patients when other biomechanical considerations are favorable.

Antegrade Versus Retrograde Stabilization

Flexible IMN stabilization of pediatric diaphyseal femur fractures may be performed in an antegrade or a retrograde fashion. For technical ease, surgeons often favor retrograde nail insertion from medial and lateral entry points. Additionally, when utilizing titanium implants, the ability to easily configure two “C”-shaped nails (Fig. 9.2a–c)—as opposed to the “C” and “S” configuration of each nail required to provide balanced implants with antegrade insertion—strongly favors distal insertion sites and the retrograde technique. However, fracture characteristics may influence the decision regarding the direction of implant insertion. Retrograde flexible IMN has been shown in a biomechanical model to demonstrate greater resistance to torsion and bending forces than antegrade nailing (350 ± 72 N/mm and 195 ± 95 N/mm stiffness, respectively; $P = 0.02$) [41, 42]. However, antegrade insertion technique provides greater resistance to femur fracture shortening over the nail construct. “C”- and “S”-configured nails inserted proximally resulted in higher load at 5 mm of shortening (417 N vs. 247 N; 69 % greater) than two “C”-shaped implants inserted retrograde. At these levels, the antegrade construct would support 95 % of the force generated by a 45 kg child as opposed to only 55 % support by the retrograde technique [41, 43]. Therefore, antegrade insertion (most often with steel nails in order to provide improved ability to configure and maintain “C” and “S” configurations) should be considered when patient weight, fracture pattern, or compliance makes axial shortening a significant risk (Fig. 9.3a, b).

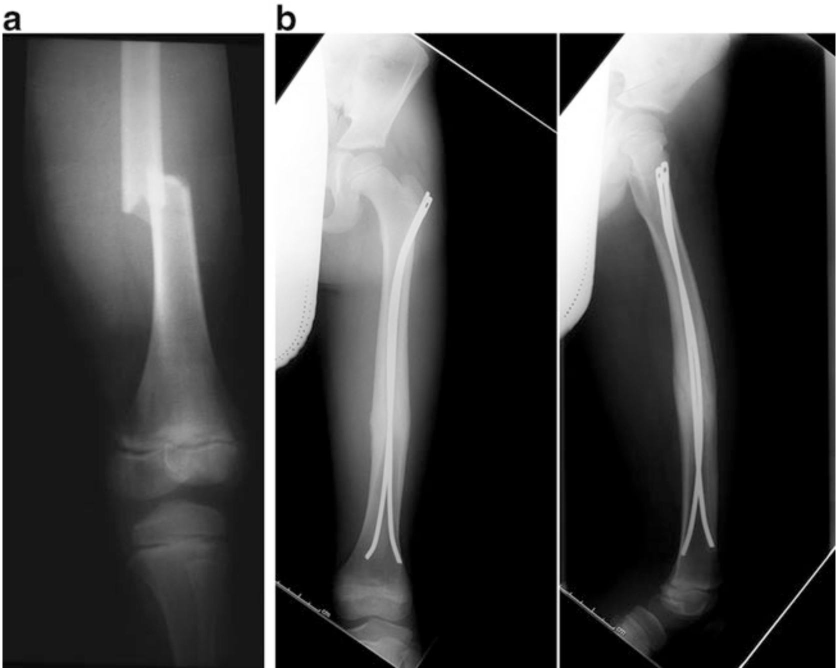

Fig. 9.3 (**a**) Injury radiographs of 8-year-old with isolated femoral shaft fracture. (**b**) AP and lateral radiographs of stabilization with stainless steel nails placed with antegrade technique through a single proximal lateral insertion

Soft-Tissue Considerations

The soft-tissue stripping and surgical debridement required when managing open femur fractures may result in increased time to union and higher perioperative complication rate when managed with flexible IMN [44]. Depending upon the fracture pattern and patient characteristics, flexible IMN may remain the optimal choice for fracture management. When adequate muscle and deep tissue are present to cover the bony structure, intramedullary fixation can provide stability with improved access for soft-tissue coverage procedures and grafting. In cases of gross intramedullary contamination, or need for bony shortening for soft-tissue management, fixation methods other than flexible IMN are preferred. Conversion to flexible IMN may be considered in the subacute setting following acute external fixation. While the risks of subsequent intramedullary infection in this setting and the influence of elapsed time interval are not well defined, reports of infection are infrequent and flexible IMN may remain an excellent option for definitive fixation.

Authors' Preferred Technique

Preoperative planning for flexible IMN use should be approached in stepwise fashion. After the appropriate patient selection has been made, based on surgical indications discussed above, there are still several decisions facing the surgeon. The first is the implant type. The biomechanical differences between stainless and titanium nails have been previously discussed. Clinically, our preference is to use stainless steel nails. We find them to be more rigid and more likely "hold" their pre-contoured positions. However, others have reported excellent clinical results using titanium nails. In our experience, using titanium nails in larger, heavier patients may not be as efficacious. We therefore reserve use of titanium implants for smaller patients, i.e., those who weigh less than 20 kg.

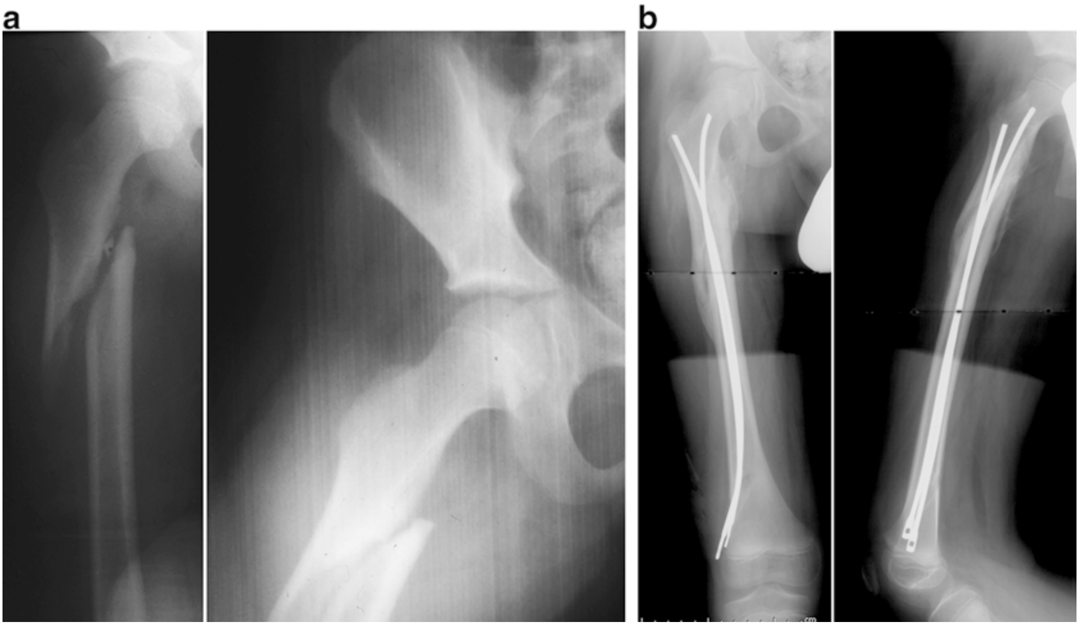

Fig. 9.4 (**a**) AP and lateral radiographs of 9-year-old with a proximal diaphyseal femur fracture. (**b**) AP and lateral radiographs of healing after stabilization with stainless steel rods placed with retrograde technique through a single distal lateral incision (note the extent to which the nails were advanced laterally)

Once the preferred implant has been selected, the next decision regarding surgical technique is patient positioning, which may include use of a fracture table or a flat radiolucent table utilizing manual traction. Regarding positioning of the patient, while a radiolucent table without traction decreases positioning time, it usually requires "an extra set of hands" to apply traction during the procedure. If this help is not available, the usual practice is to position the patient on a fracture table to allow the fracture to be reduced prior to draping.

Finally, once the appropriate implant and patient positioning have been finalized, the surgeon must determine whether to use a single lateral-entry port with nails shaped in "S" and "C" configurations or two insertion sites distally, which requires one medial and one lateral insertion site. If a single lateral insertion site is utilized, the rods are introduced into the "long segment," with one rod pre-bent into an "S" shape, and the other in a "C"-shaped fashion (Fig. 9.4a, b). Our belief is that the rod contact in the isthmus of the long fragment provides long fragment fixation while the "S"- and "C"-shaped stainless steel rods flaring at the metaphysis provide "short fragment" fixation. With each fragment fixed and the femur restored to length, the periosteum functions as a "Chinese finger trap" and provides additional stability. We believe that stainless steel rods are best suited for the single lateral insertion technique. In our experience, titanium rods are less likely to maintain the "S" and "C" shapes.

The advantages of a single lateral insertion site are a single lateral incision, potentially less operative time, and avoidance of an implant in the medial distal femur. In our experience, these implants in the medial distal femur femur, when left prominent, may cause pain in the area of the distal VMO and frequently require implant removal.

The starting hole for the single lateral insertion technique is the end of the metaphyseal flair of the lateral aspect of the proximal or distal femur. The incision should start here and should extend away from the fracture site, as the majority of the incision will be used to provide soft-tissue relief from the direction that the rod is introduced. We use a cannulated 9 mm reamer to make a starting hole with careful attention to insure that the reamer is positioned in the mid-axial plane. When using this reamer, particularly in the smaller child, care must be taken to insure that it does not penetrate medially, anteriorly, or posteriorly, as the canal can be small in diameter in younger patients. Next, the appropriate diameter rod is selected. As previously discussed, a nail diameter that will allow "80 % fill" has been recommended. However, it should be noted that if too large an implant is chosen it may not be possible to advance the nails, or they may lead to further comminution or propagation of subtle or sub-radiographic fracture lines. We have not encountered problems when using stainless steel rods of different diameters, although this has been reported as a risk factor for complications with titanium nails [25]. We use a Kocher clamp to hold the nail in place over the femur to estimate appropriate nail diameter and length. When using a single insertion site, we usually place the "S"-shaped nail first. When placing nails distal to proximal, we will attempt to place the "S"-shaped nail as proximal as possible into the femoral neck. When advancing the second nail, it is important to be aware that the second nail can "bind" the first and unintentionally advance it at the same time. As the nails are placed into their final position, the surgeon should be mindful that they may protrude through the metaphysis, and must pay particular attention to fluoroscopy in the lateral plane. As a final step following retrograde nail insertion, the knee should be flexed fully to disengage any muscle or fascia that may be entrapped below the implants. Tension within the extensor mechanism that results from the hyperflexion maneuver will free any tissue from below the rods and ensure that the patient will not encounter pain or restriction of tissue motion that could contribute to decreased active extension and lead to a knee flexion contracture postoperatively.

Postoperative Considerations

Immobilization and Weight Bearing

Postoperative management of pediatric diaphyseal femur fractures managed with flexible IMN is influenced by patient age and weight, fracture pattern, and intraoperative assessment of construct stability. With stable fracture patterns and in patients less than 45 kg, weight bearing is generally started immediately, as tolerated by the patient. While evidence for or against early weight bearing is lacking, some authors advocate waiting 4–8 weeks before allowing full weight bearing [4, 12]. A knee immobilizer has been advocated for use by some authors and has been proposed as an adjunct to decrease pain until callus is radiographically visible [34]. Additionally, a single-leg spica for 4 weeks may be considered as an added measure of stability when fracture pattern, implant stability, or compliance is in question [35]. When early callus is visualized on both AP and lateral radiographs, patients may be advanced to full-unassisted weight bearing as early as 2–4 weeks.

Indications for Physical Therapy

There is no current data to support the use of physical therapy following pediatric diaphyseal femur fracture fixation. The AAOS clinical practice guideline project produced a neutral statement on physical therapy, in which the panel was "unable to recommend for or against its use" [16]. In our experience, physical therapy is seldom needed to allow an expeditious return to activities of daily living. However, it may be indicated in cases of significantly decreased knee range of motion beyond 3 weeks postoperatively or in cases of extensive soft-tissue injury. Additionally, when child and family are interested in optimizing return to sporting activities in a timely fashion, physical therapy and subsequent performance training may be indicated to optimize the running gait, and sport-specific strength training and agility exercises. While poorly studied in the literature, safe return to sport following flexible IMN for pediatric femur fracture is often possible approximately 3–4 months postoperatively. To provide clearance for unrestricted return to sport, we require mature bridging callus on AP and lateral radiographs, and 85 % range of motion and lower extremity strength compared to the normal, contralateral side.

Indications for Implant Removal

There is no clear consensus regarding the indications for removal of asymptomatic flexible IMN following diaphyseal fracture union. The AAOS clinical practice guidelines project found insufficient evidence in literature review to make a recommendation for or against routine removal [16]. As growth occurs, the position of the implant within the bone changes relative to the metaphyseal-diaphyseal junction and may theoretically act as a stress riser and increase fracture risk during subsequent loading. Advantages of nail removal are the elimination of these stress risers and the prevention of potential nail irritation within the soft tissue as the implant position changes relative to the metaphyseal flare as the "cut back zone" remodels during growth. These issues may be seen particularly with distal metaphyseal insertion sites, where the greatest amount of longitudinal bone growth occurs. In addition to implant position changes with growth, leaving the nails long at the time of insertion or fracture shortening that may cause implants to slide distally may lead to tissue irritation around the knee that may represent an indication for nail removal. Notably, this skin irritation or superficial infection at the nail insertion site is the most commonly reported complication of flexible nail use in pediatric femur fixation and is reported in 8–52 % of cases [49–52]. Flexible IMN removal may be performed safely when mature union has occurred, often by 6 months postoperatively. Removal surgery has a reported complication rate of <3 %, with superficial infection being the most commonly reported complication [53].

Residual Deformity

The results of flexible IMN treatment for diaphyseal pediatric femur fractures are generally quite good. Residual deformity is the most common reported significant complication. While angulation and malrotation may occur, shortening is the most commonly reported complication [2, 10, 13, 14, 25, 54]. Length-unstable fracture patterns, weight over 45 kg, and age over 10 years may result in higher rates of unacceptable shortening [52, 55–58]. With flexible titanium nail use, an increase in anterior bow on average of 15° has been reported in as high as 16 % of patients [59]. In one series, rotational asymmetry of 15° or greater was reported in 47 % of cases when utilizing titanium IMN [60]. In one study, while minor complications of skin irritation or breakdown were no different, significant complications such as angulation or nail irritation requiring revision surgery were decreased when using steel flexible IMN as compared to titanium for pediatric diaphyseal femur fractures [33].

Conclusion

Fixation for treatment of pediatric diaphyseal femur fractures in the school-age children allows mobilization and decreases the burden of care. Flexible intramedullary nailing has been proven as an effective technique for pediatric diaphyseal femoral fracture fixation, particularly in the 5- to 11-year-old age group. Careful consideration of fracture pattern will allow the use of this technique while minimizing the risk of unacceptable shortening. Length-stable fracture patterns with a primary transverse component and minimal comminution are the patterns most amenable to fixation using flexible IMN fixation. Additionally, patient weight less than 45 kg has been correlated with decreased risk of deformity and shortening.

While the increased stiffness and ability to place "locking" screws through the eyelet of steel (Enders) IMN may allow fixation without deformity in some more unstable patterns or in larger children, attention to technical considerations of nail size, direction of entry, and nail configuration are critical to optimizing outcome when using titanium or steel IMN. Current biomechanical and clinical data may support the use of either steel or titanium IMN, and diaphyseal fractures may be managed successfully with either implant. A combined diameter for the two nails of > 80 % of the narrowest canal diameter measurement has been recommended for maximal stability to prevent shortening and angular deformity. Retrograde flexible IMN has been shown in a biomechanical model to demonstrate greater resistance to torsion and bending forces than antegrade nailing. However, antegrade insertion technique may provide greater resistance to femur fracture shortening over the nail construct. Therefore, antegrade insertion may be considered when patient weight, fracture pattern, or compliance makes axial shortening a significant risk.

Generally, patients may be mobilized rapidly following flexible IMN fixation of diaphyseal femur fractures. Weight bearing is allowed for stable fracture patterns and a knee immobilizer may be used for comfort as needed. Occasionally, a short-term single-leg spica may be considered as an added measure of stability when fracture pattern, implant stability, or compliance is in question. Return to activities beyond those of daily living is allowed as mature callus is visualized at approximately 4 months, though timelines are dependent upon patient age and fracture characteristic. While formal physical therapy for strengthening may be helpful for expeditious return of symmetric thigh function, there has been no demonstrated benefit of routine organized physical therapy following pediatric diaphyseal femur fracture fixation.

When utilized with appropriate indications for length-stable patterns and in children weighing less than 45 kg, good outcomes may be expected following flexible IMN fixation of diaphyseal pediatric femur fractures.

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10

Treatment of Pediatric Diaphyseal Femur Fractures with Plate Fixation

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and Daniel J. Hedequist

Introduction

The use of submuscular plates for pediatric femur fractures has become more common in the last 10 years [1–3]. While multiple surgical options exist for this injury in children older than age 5, titanium elastic nailing for fractures has gained the most widespread use, due to ease of insertion, rapid healing, and satisfactory outcomes. However, the use of elastic nailing for length-unstable fractures (oblique or comminuted fractures) has been shown to be associated with unacceptable complications such as shortening, malangulation, and nail migration [4]. Rigid intramedullary nailing through a lateral trochanteric entry point was developed because elastic nails were suboptimal for length-unstable fractures. Excellent clinical results have been obtained with these more rigid implants. However, the frequency and clinical sequelae of potential complications following entry into the proximal femur have not been fully elucidated to date and may include proximal femoral growth arrest and avascular necrosis. Submuscular plating for pediatric femur fractures evolved in order to overcome the stability problems with flexible nails in length-unstable fracture patterns while also avoiding the need to perform reaming of the greater trochanter with rigid intramedullary implants. Open compression plating, while occasionally still needed, has largely been supplanted by the more minimally invasive submuscular bridge plating technique. The use of rigid intramedullary implants will be discussed elsewhere in this book; this chapter focuses on submuscular plating for pediatric femur fractures, with a shorter discussion on open femoral plating.

Submuscular Plating: Patient Selection

Fracture pattern, patient size, and patient age are all determining factors for selecting the mode of fracture fixation. The typical patient for submuscular plating is a patient with significant growth remaining (in whom concerns regarding rigid nailing might arise) who has an inherently length-unstable fracture pattern (for whom flexible nailing may be associated with suboptimal results) [5]. Spiral fractures, comminuted fractures, and fractures with butterfly fragments which may potentially shorten, rotate, and angulate with flexible nailing are better suited for submuscular

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plating [4]. While such complex fracture patterns are suitable for submuscular plating, transverse fractures may be best suited for nailing, as these are inherently more difficult to treat with a submuscular plate, given that translation in the anterior-posterior direction on the lateral fluoroscopic view can be difficult to reduce with submuscular plates.

In general, most patients who require operative intervention who are over 5 years of age may be treated with a plate regardless of size, given the variety of plate lengths available. Obesity and resultant increased thigh circumference may be detrimental to the ease of submuscular plating, as the placement of percutaneous screws is made more difficult, given the fixed length of drill bits and screwdrivers. In a very obese child, other fixation methods should be considered, including rigid retrograde femoral nailing. In the authors' own experiences, this is a rare occurrence and usually an issue only in an older obese adolescent.

Typically, the age of the patients best suited for submuscular plating is between 5 and 12 years. After 12 years of age, lateral entry trochanteric nailing may be the best form of treatment, given the size of the patients, length of the femur, and relative safety of trochanteric entry for proximal reaming, with regard to avoidance of avascular necrosis risk. Prior to that age, it still remains unclear what effects nailing will have on the proximal femoral anatomy and blood supply.

Fracture location may dictate the choice of implant and the surgical technique; however submuscular plating may be utilized for subtrochanteric fractures, diaphyseal fractures, or distal metaphyseal fractures [1, 6]. The technique, as discussed below, is similar for each of these locations and only varies with regard to plate contouring and the potential use of locking screws.

Submuscular Plating: Technique

Patient positioning and implant choice are important factors to consider prior to surgical incision. The use of a fracture table greatly aids in obtaining a preliminary reduction and obviating the need for an assistant for manual traction when using a radiolucent table. We have found placing the patient supine, with the legs in a scissored position on a fracture table, to be most beneficial. Prior to beginning the case, it is necessary to check both the preliminary reduction as well, to ensure that the entirety of the femur can be seen fluoroscopically in both the anteroposterior and lateral planes. Radiographic check of both the hips and the knee can also help to assess the rotational alignment of the femur, as it remains critical to match the rotational profile to the contralateral side. As a general rule, translation or angulation of the femur on the anteroposterior views can be corrected intraoperatively by bringing the fracture fragments to the plate. Significant translation on the lateral view is very difficult to correct and maintain intraoperatively and must be addressed prior to incision. Because the ideal fractures for submuscular plating are oblique or comminuted, traction on the limb will generally bring the fracture into reasonable alignment. Transverse fractures which have sagittal and coronal translation are optimal for a variety of nail choices, but are much more challenging for submuscular plating, as correcting both planes at one time while trying to affix the plate is difficult. Overall, restoring anatomic femoral rotation and alignment are the keys to successful treatment.

The choice of implants is most influenced by equipment available to the surgeon in the operating room. Typically, the standard plates we have used are 4.5 mm combination plates (with holes allowing for either standard screw fixation or locking screw fixation). Narrow plates without any anterior bow have generally been acceptable, though the surgeon must keep in mind normal femoral anatomy, and adjust plate position relative to the shaft with these principles in mind. For example, the bridged portion of the femur, which typically involves the fracture line and possibly comminuted fragments, may align with the more anterior aspect of the plate, when seen on a lateral radiograph. Broader plates are often too large for many pediatric and adolescent femurs, and the extra rigidity usually is not needed. In general, locking screws are also not needed in healthy patients, given the excellent bone quality. Pre-contoured plates with an anterior femoral bow are available, but we have found the standard plates to fit reasonably in most patients. The lengths of plates used depend on the size of the femur, but having available lengths from 10 to 16 holes will usually suffice. As a general rule, the length of the plate should be from just above the lateral distal femoral physis distally to just below the flare of the greater trochanter proximally.

The majority of cases for femoral shaft fractures will be treated with the plate inserted in retrograde fashion from a starting point just above the lateral distal femoral physis. Alternatively, subtrochanteric fractures should be treated with a plate inserted in an antegrade fashion along the lateral aspect of the greater trochanter. Initial exposure starts with a 2–3 cm lateral incision followed by division of the iliotibial band. When possible, we prefer a distal starting point, which can easily be accessed by lifting up the distal aspect of the vastus lateralis. The next step in treatment is crucial to develop a subvastus plane, which is inherent in the technique, rather than attempting to establish a plane subperiosteally. With the assistant elevating the distal vastus anteriorly and laterally, the surgeon meticulously advances a Cobb proximally as far as possible under the vastus and onto the femur extaperiosteally. This step will create a surgical plane to later allow the plate to slide smoothly and atraumatically up into its resting position prior to fixation.

Once the proper plate size has been chosen, the plate can be held against the femur while assessing from an A-P radiographic, which informs contouring of the plate. The flare of the distal femoral lateral metaphysis must be bent into place with a heavy table-top bending press,

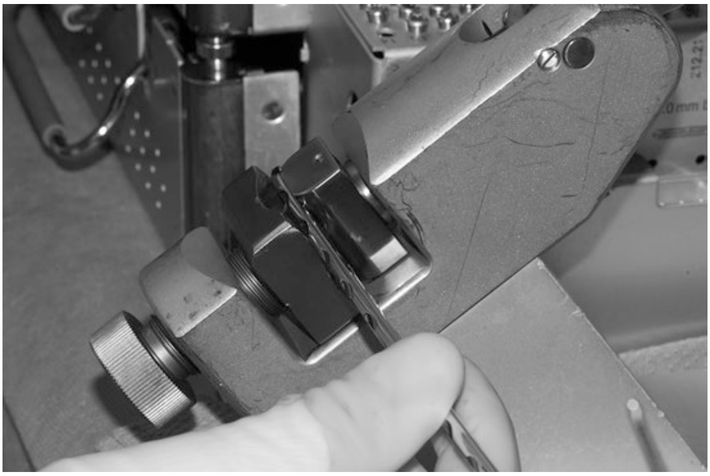


Fig. 10.1 Intraoperative photograph of plate bender used to obtain contour of metaphyseal region

Fig. 10.2 Photograph showing small incision used to lift up vastus and tunnel plate in extraperiosteal manner

Fig. 10.3 Fluoroscopic image obtained during tunneling of plate proximally; notice the edge seen in parallel confirming correct position against the femur. The plate lies off the femur below; this will be brought back to the femur with screw fixation

Fig. 10.4 Radiograph of a patient who underwent submuscular plating of a distal fracture; notice that the contoured plate lies anatomically against the femur

taking care not to over- or undercontour the plate (Fig. 10.1). Once contoured, the plate can be tunneled up the side of the femur with a few technical points to consider (Fig. 10.2). The plate should be checked occasionally under fluoroscopy to ensure that the tip maintains contact with the femur and that it is not sliding anteriorly or posteriorly. This would be evident fluoroscopically as the plate overlapping the femur rather than against the lateral aspect (Fig. 10.3). Once the plate has been tunneled to the final position, it should be close to against the femur, although any translation of the plate away from the bone can be remedied with fixation of the screw. It is also crucial that if a metaphyseal flare was bent into the plate, this bend should lie at the level of the metaphyseal flare in the anteroposterior plane; if you insert the plate too far then the flare will not match and the fracture is pushed into valgus or varus (Fig. 10.4).

Checking the plate on the lateral view will then serve two purposes. First, assessing any anterior or posterior translation of the plate allows for correction by pulling the plate back and redirecting, or by using a Kirschner wire to translate it down to the femur. Second, the distal aspect of the plate must be aligned with the distal femur, as the tendency is for the distal edge to be too anterior, which is easily remedied as the distal edge is exposed at the insertion site and can be manually pulled posteriorly. Continuing in the lateral fluoroscopic view, the next step is percutaneous advancement of stout k-wires through the most proximal and distal holes, then pulling the plate up or down, as appropriate, and drilling the k-wires into bone to hold plate position (Fig. 10.5).

Next, screws should be placed, the location of which should be determined by the fracture and position of the plate. As a general rule, the first screw should be placed in the fracture fragment which lies farthest away from the entry site of the plate and should be placed in a hole which is closest to the fracture site. Screw placement is done by obtaining a lateral fluoroscopic view and

Fig. 10.5 Intraoperative photo documenting a k-wire placed through the distal plate, holding the correct rotation and translation of the plate

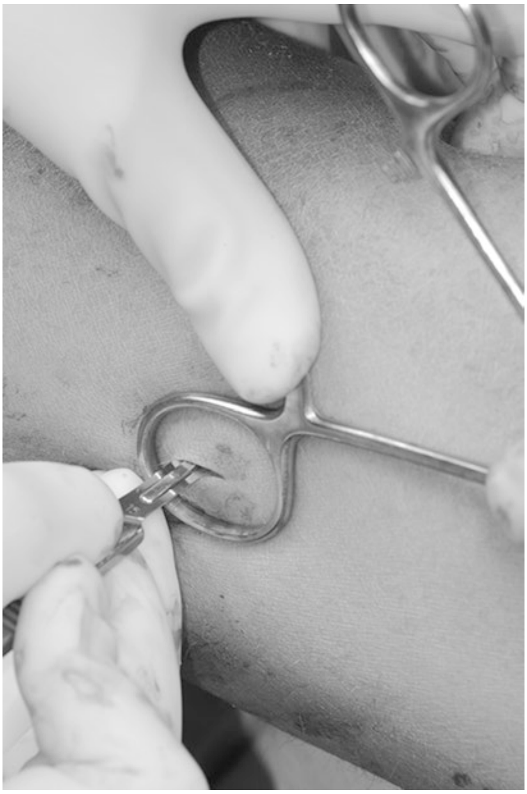


Fig. 10.6 Intraoperative photo showing the stab wound used for percutaneous screw placement

making a 1 cm stab incision deep enough to cut through the IT band (Fig. 10.6). This is followed by placing a snap and spreading the incision and IT band for ease of entry of the drill bit and screw. A standard drill bit is used without a drill guide. Placement of the drill bit through the hole and down to bone is then performed after a quick fluoroscopy check to assess position (Fig. 10.7). The drill must be then angled perpendicular to the femur and drilled bicortically. Once drilling is complete, the drill bit should be left in place and the depth gauge should be used fluoroscopically on the AP view to assess length by placing it over the thigh and measuring from medial to lateral cortex (Figs. 10.8 and 10.9). The screw length for the first screw should take into account the distance that the plate is translated from the bone since the first screw is used to bring the plate down to the cortex and will only work if the far medial cortex gets engaged. Frequently, this first screw length is slightly long, and may be eventually replaced with a shorter screw (Fig. 10.10a, b). Prior to placing the screw, it is necessary to tie a heavy undyed vicryl suture around the base of the screw head, so that screws that get placed along an aberrant path or that slide posterior can be easily retrieved by this “safety rope” (Fig. 10.11).

The second screw then is placed in the similar manner; usually the location of the screw is close to the fracture site on the opposite fragment as the first screw (Fig. 10.12). The placement of all screws is similar in nature and the amount of screws placed is variable. In younger children (e.g., ≤8 years old), having two screws on either side of the fracture is often sufficient. In older preadolescents (≥9 years old) the placement of three screws on either side may be warranted (Fig. 10.13). The biomechanical principles behind AO technique support having adequate spread between the screws and having a screw in the proximal and distal fragment as close to the fracture site as possible. The placement of “lag” screws or screws into butterfly fragments is usually not warranted, since the fracture fragments are not stripped off the thick femoral periosteum unique to the pediatric population.

Subtrochanteric fractures, as mentioned above, are also well suited for submuscular plating, and a few points warrant discussion. The insertion of the plate should be performed from a proximally based incision. The dissection is carried

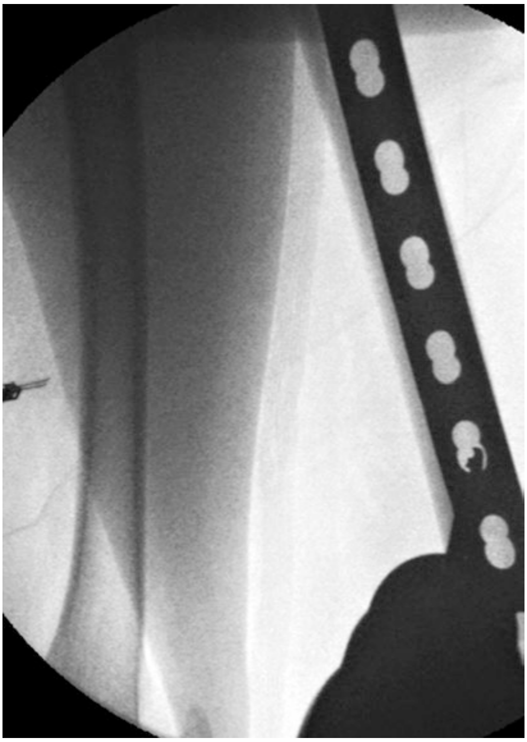


Fig. 10.7 Lateral fluoroscopic image showing the correct placement of the drill through the combi hole in the plate

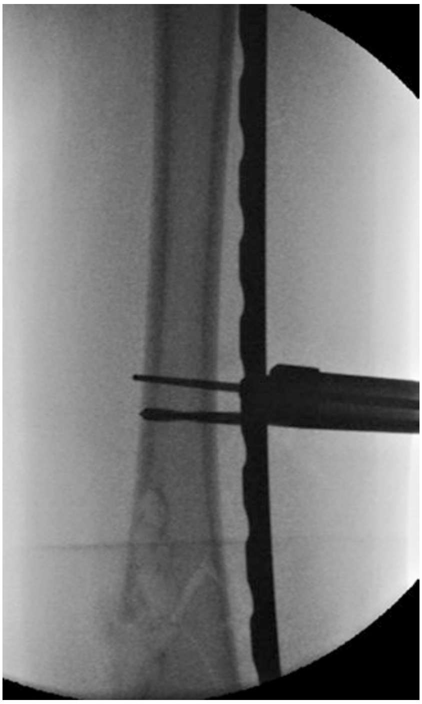


Fig. 10.9 Fluoroscopic image of the depth gauge used over the thigh in order to gauge length of screw needed. In this scenario, the screw must be long enough to engage the far cortex if it is to bring the plate down to the bone

Fig. 10.8 Clinical photograph documenting the use of the depth gauge over the thigh to confirm depth of screw by fluoro shot

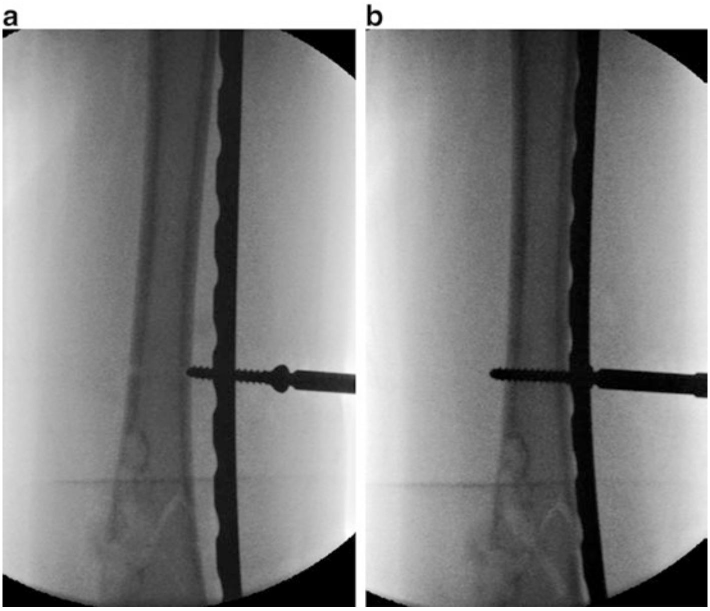


Fig. 10.10 (**a**, **b**) Two intraoperative fluoroscopic images showing the ability of a correctly placed screw to reduce the plate down to the femur

Fig. 10.11 Intraoperative photo of a screw being placed percutaneously; note the vicryl tie suture which is attached to the screw head as a safety measure in case the screw slips out posterior to the femur

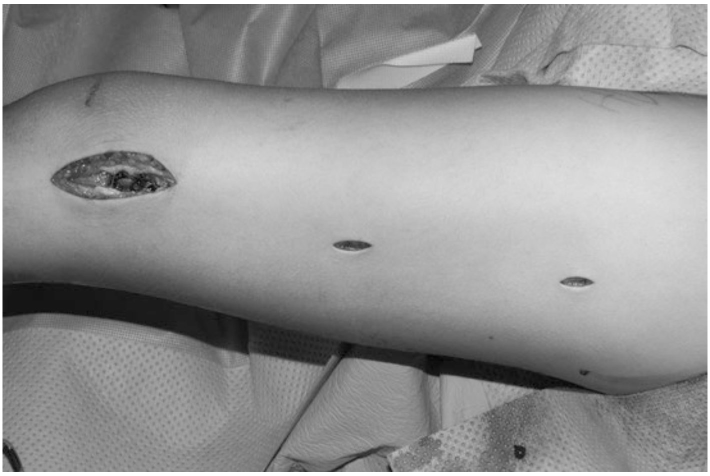


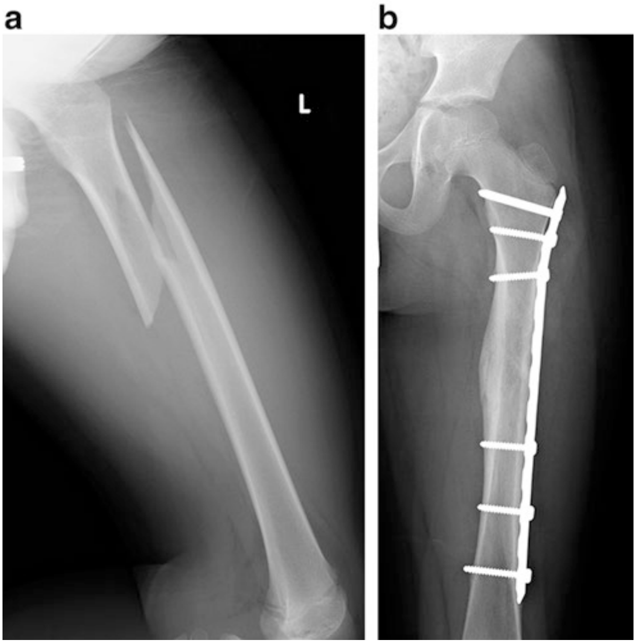
Fig. 10.12 Clinical photograph of the thigh after successful fracture reduction and stabilization from submuscular plate application

through the IT band, and the vastus can be lifted off extraperiosteally from the vastus ridge. Contouring of the plate should match the trochanteric flare and the plate distally should stop above the metaphyseal distal flare so that no distal contouring is needed. In subtrochanteric fractures, the use of 4.5 narrow combination plates is preferred, as these plates allow for proximal locking screws. The plate and first two screws are placed as described previously. Once the fracture is reduced, a proximal locking screw is placed in the superior hole percutaneously using the locking drill guide followed by screw placement. With subtrochanteric fractures it has been our practice to have at least two screws proximal to the fracture, the first being bicortical and non-locking, which compresses the plate to the bone, and the second being a locked screw in order to increase proximal fixation strength (Fig. 10.14a, b).

Fig. 10.13 Radiograph documenting the anatomic alignment of the femur

Distal metaphyseal or metadiaphyseal fractures are fixed using similar techniques. These fractures are best suited for distal locking screws, given the relatively softer metaphyseal bone and the limited placement of screws due to the proximity of the distal physis. These plates also need to be contoured appropriately to the anatomy, as incorrect contouring can force distal fractures into varus or valgus. Frequently, the screws on the distal fragment are all locking screws. Therefore, the first non-locking bicortical screw in the proximal fracture fragment remains critical

Fig. 10.14 (**a**, **b**) Radiographs of a patient with a subtrochanteric fracture which was fixed by a proximally based incision



to bring the plate down onto bone. If correctly contoured, the plate will lie directly against the bone and locking screws can be easily placed. If the plate still remains off of the bone distally, then placing a standard screw in the distal fragment may be necessary prior to distal locking-screw placement.

Following submuscular plate fixation, younger patients do not require any postoperative immobilization and can be managed with early knee range-of-motion exercises and quadriceps strengthening prior to weight bearing. In older children, weight bearing generally needs to be delayed until significant healing has occurred radiographically, given that the plates are load bearing and cannot tolerate the stresses of weight bearing in isolation. Frequently, gradual advancement of weight bearing in older children is initiated between 8 and 10 weeks postoperatively, with younger patients starting at 6–8 weeks. Given the rigidity of fixation, pain relief from fracture movement is generally rapid, and most patients restore knee motion within 2 weeks of the operation. Knee immobilizers can occasionally be helpful for children who experience postoperative pain or apprehension with motion, but are not used routinely.

Complications

Complications following submuscular plating are rare and mostly avoidable. Malreduction of fractures is usually due to either distal location of the fracture or severe comminution combined with iatrogenic error. Distal fracture malreductions may be due to either inappropriate contouring or misplacing a properly contoured plate. This can be avoided by contouring the plate template to the other side and making sure that the plate contouring is based on the plate lying just superior to the physis. Both overcontouring and placing the contour too proximal will drive the reduction into valgus. Alternatively, leg length inequality can be seen with non-anatomic fixation in the setting of significant comminution, the risk for which can be minimized by preoperatively measuring the other side.

Late complications have been described and are related to plate retention in the growing child [7]. In patients with significant growth remaining, the plate will grow proximally with the femur. Proximal migration with growth then leads to the metaphyseal contour of the plate migrating proximally while the bone remains affixed to the plate, leading to a valgus deformity. We have theorized that this occurs because the contoured portion of the plate eventually lies in an area where the femur is usually straight. With this migration, the distal metaphyseal screws also migrate to thinner segment of normal femur, causing them to eventually protrude into the medial thigh soft tissues, which causes irritation. These complications can be avoided by vigilant monitoring (despite complete fracture healing and full return to function) or empiric plate removal at 6–12 months postoperatively in children with significant growth remaining [7, 8]. While potentially bony overgrowth is a documented problem that makes plate removal difficult, our clinical experience is that this can be done easily as a day surgery procedure with minimal risk or complications [9].

Open Plating

Open plating of pediatric femur fractures, while now an uncommon procedure, still occasionally may be needed. Standard compression plating originally gained popularity due to the rigid fixation and ability to mobilize trauma patients with head injuries. Encouraging results spurned more widespread use with acceptable results in children. Advantages of compression plating included anatomic reduction, rapid mobilization of the patients, and a high union rate. The immediate disadvantages of compression plating include prolonged operative time, increased blood loss, larger scars, and the potential need to remove the plate through larger, more invasive incisions. Further investigation and follow-up showed that most patients developed limb overgrowth on the operative side. It was hypothesized that the exposure and periosteal stripping needed for fracture reduction and plating caused overgrowth of that side. Concerns of overgrowth as well as the evolution of intramedullary fixation, and now submuscular plating, have decreased the numbers of patients who require open plating.

Currently, open plating is recommended in open fractures with severe or contaminated wounds which require irrigation and debridement of the fracture through an extended exposure. In these cases, the exposure required for plating can easily be done at the same time and compression plating is an ideal choice. Ideally, a narrow 4.5 mm compression plate should be used, obtaining six cortices of purchase above and below the fracture site. It has been our practice to place these children in a lateral position if the open wound can be accessed, given the ease of exposure with retraction of the vastus. Traditional plating techniques are applied after thorough irrigation and debridement of the fracture. One of the keys to the procedure is neuromuscular blockade of the patient, given that getting the fracture out to length can be difficult. Open fractures with significant comminution may be difficult to plate, given that determination of length and rotation can be challenging and may be better suited for provisional or definitive external fixation or nailing.

In our experience, fractures in patients with cerebral palsy due to osteopenia and spasticity or in children with underlying osteomalacia may also be best suited for open plating. These nonambulatory patients are best treated with techniques which allow rigid fixation, do not require immobilization, and allow for quick return to seating. Femoral shaft fractures or fractures above or below previous implants placed for osteotomy are common in this population given their osteopenia. In these patients, we recommend lateral decubitus position with an open standard lateral exposure. We have found that using locking plates greatly enhances fixation and lessens implant failure compared to traditional implants. Given the spasticity of the patient and the osteopenia, placement of an extra amount of screws is needed in order to avoid any need for postoperative immobilization (Fig. 10.15a, b). We have not found submuscular plating to be effective in these patients, given their spasticity and the contractures which make positioning difficult. Obtaining a reduction by using the screw to pull the plate to bone is not always possible.

Fig. 10.15 (**a**, **b**) Radiographs of a patient with cerebral palsy who sustained a femur fracture. The patient was treated successfully with a standard open approach, lag screw fixation, and locking plate fixation

Summary

The use of submuscular plates for pediatric femur fractures has been shown to be safe and efficacious. In our experience, the optimally indicated patient is usually between the ages of 5 and 12, with a length-unstable diaphyseal fracture. Subtrochanteric fractures and distal fractures are also well suited for submuscular plating with locking plate technology to improve fixation in the shorter fragment. The complications associated with submuscular plating are predictable and mostly avoided with attention to proper contouring and placement of the implant in all patients, and with close monitoring or plate removal in growing children. Open plating, although rarely indicated, remains an option with open fractures or in children with spasticity and compromised bone.

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11

Treatment of Pediatric Diaphyseal Femoral Fractures with Locked Intramedullary Implants

Jonathan Phillips, David D. Spence,
and Derek M. Kelly

Introduction

The introduction of intramedullary fracture fixation during the Second World War is credited to Gerhard Kuntscher in 1939. Almost 75 years later this technique has been adapted to be widely applicable to the treatment of femoral fractures in older children and adolescents. The last two decades have seen a shift in the management of this relatively common injury. The technique of traction and casting has given way to operative intervention, with outcomes that have not always been better than the benchmark nonoperative techniques [1–4]. Complications of operative treatment of femoral fractures in children include several not seen in adults: avascular necrosis (AVN) of the capital femoral epiphysis, valgus growth disturbance at the knee, and refracture after external fixation (Fig. 11.1). The enthusiasm for shorter hospitalization, early mobility, and the problems that have been associated with traction and casting (for example, malunion and shortening) has created a new set of problems, which must be ameliorated to justify a shift in management. This chapter discusses the basic scientific underpinnings of locked intramedullary nailing of femoral fractures in children, the indications, operative technique, risks, and shortcomings.

Anatomical Considerations

The growing femur has three physeal areas: the distal femoral physis, the apophysis of the greater trochanter, and the capital femoral physis. The distal femoral physis contributes to the greatest length of the femur. A growth disturbance potentially will result in either a femoral length discrepancy or an angular deformity. Vascular disturbance of this physis and epiphysis is, however, rare possibly because of the abundant circulation from the geniculate anastomoses.

By contrast, the capital femoral epiphysis is highly vulnerable to vascular insult. The lateral epiphyseal branch of the medial circumflex artery is the dominant circulation to the epiphysis prior to physeal closure (Fig. 11.2). It courses through the piriformis fossa and up along the neck of the femur, bypassing the vascular obstruction of the physis, a structure that has no perforating vessels

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Fig. 11.1 Fracture after external fixation

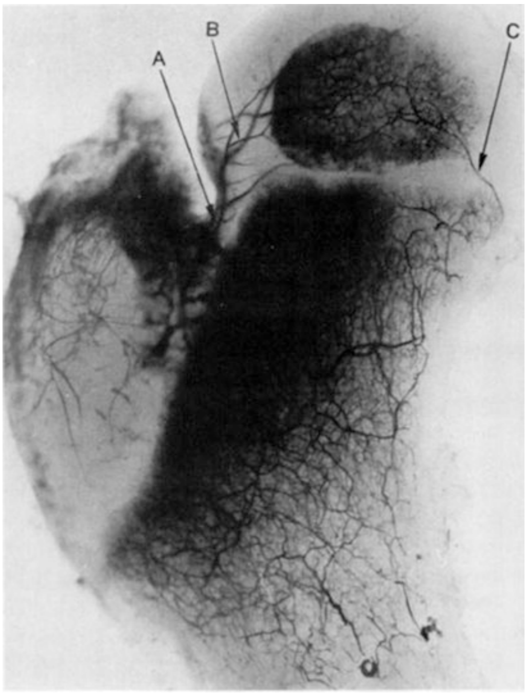

Fig. 11.2 The lateral epiphyseal artery is labeled *B* in this radiograph. Reprinted with permission from Journal of Bone and Joint Surgery Amercian, 1976, 58, The arterial supply of the developing proximal end of the human femur, Chung, 961–970

until it closes at maturity. Injury to the lateral epiphyseal artery may be sufficient to cause AVN, as no metaphyseal vessels within the femoral neck penetrates the physis. The reason that this does not occur universally is not known; however it is possibly due to the blood supply from the artery of the ligamentum teres.

The physis at the greater trochanter often is referred to as an apophysis, the purpose of which is not merely for muscle attachment. The apophysis is an important structure that maintains the head-neck offset, contributes to proper neck-shaft ankle, and provides a biomechanical lever for the abductors. The growth cartilage of this structure is actually confluent with the capital epiphysis in the neonate [5].

As growth occurs, the two physes go their separate ways, the capital physis contributing to a highly contoured ball-and-socket joint, and the trochanteric physis contributing less and less to the growth of the hip area until it closes at maturity as it assumes its role as the area of attachment of the hip abductors. However, damage to the trochanteric physis, if it occurs early enough, can produce significant geometric changes at the proximal femur [6, 7].

After the age of 8 years, the risk of these changes decreases [8], although if a large enough hole is reamed in the trochanter, particularly on its medial side, then both growth disturbance and AVN may supervene. It would seem, therefore, that growth disturbance of the greater trochanter is dose dependent, varying with the severity of mechanical insult, and that vascular damage to the epiphysis is an all-or-nothing phenomenon. Growth disturbance of the greater trochanter can be treated by corrective osteotomy, but vascular damage to the epiphysis is a devastating complication that may, if severe, be uncorrectable.

For the foregoing reasons, any intramedullary device used to fix a femoral fracture in a growing child must respect the anatomy and physiology of the immature skeleton: the entry point proximally must avoid the piriformis fossa. In the rare instance when a retrograde transarticular nailing is performed, it should be reserved for older adolescents close to skeletal maturity, and the smallest nail that achieves good fracture stability should be used.

Biomechanical Considerations

The femur is a modified hollow pipe. Weight-saving considerations have presumably conferred evolutionary advantages in animals that have led to this design. As the diameter of a long cylinder increases to accommodate greater load, the weight of the cylinder itself increases as the third power of the increased diameter. Weight can be decreased by a central canal filled with less compact bone, and by increasing the wall thickness of the tube strength can still be maintained (Fig. 11.3) [9].

For a perfect elastic column, the load-to-failure is given by the formula attributed to the eighteenth-century mathematician, Euler (1707–1783):

$$Pcr = \frac{\Pi^2 EI}{4L^2}$$

In this relationship the critical load-to-failure, *Pcr*, is directly proportional to the Young's modulus, *E*, and the bending moment of inertia of the column, *I*. It also is inversely proportional to the *square* of the length of the column. Thus, a longer column is more easily bent, which is intuitive, but Euler formalized this idea. Compensating for this greater vulnerability with increasing length is an opposing factor, which effectively strengthens the column: the bending moment of inertia, *I*, increases as the fourth power of the radius, more than compensating for the weakening effect of greater length. Again, it is logical that a long slender structure is easier to bend than a short thick one. The implications of this mechanical concept are, however, fundamental for femoral implant design. While this simple model of column failure is probably too naïve for the complex anatomy of the modified hollow tube that is the femur, it is fairly accurate for the simplest of intramedullary implants. Their resistance to failure can be manipulated a little by changing the Young's modulus (though stainless steel and titanium, the most common metal used in orthopedic implants have an *E*, which is very similar), rather more by decreasing the length of the implant (which is impractical in a long bone that needs a length-matching implant), and greatly by changing the diameter of the implant. The weakest implant is a small-diameter long titanium nail (i.e., 2 mm). The strongest is a stainless steel nail of 6 or 8 mm in diameter. This approaches

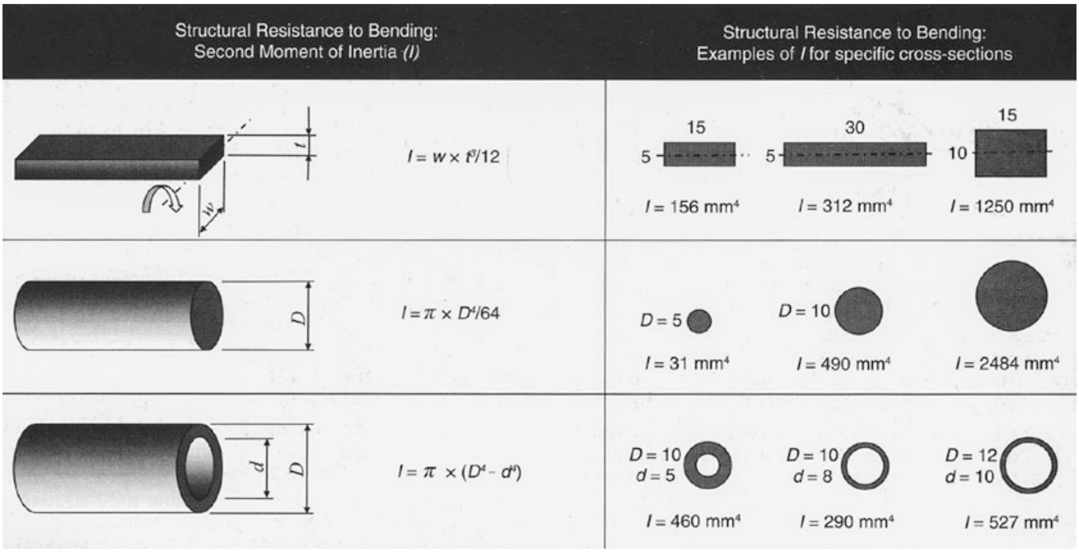

Fig. 11.3 Influence of cross-sectional geometry on bending stiffness of basic structures, e.g., increasing the outer diameter of a cylindrical structure from 10 to 12 mm while retaining a wall thickness of 2 mm increases bending stiffness (*I*) by 82 %. Reprinted with permission from Bottlang M, Fitzpatrick DC, Augar P: Musculoskeletal Biomechanics, in Flynn JM (ed): Orthopaedic Knowledge Update: 10. Rosemont, IL: American Academy of Orthopaedic Surgeons, 2011, pp 59–72

the dimensional capacity of the isthmus of a child's femur.

Thus, the biomechanical concepts outlined above explain some of the behavior both of a femur under load and of the implants used to treat this bone when those loads are exceeded.

Implant Design Considerations

It can be seen from the foregoing that implants designed for stabilization of femoral fractures in a growing child should have at minimum the following characteristics: (1) design optimized for the proximal femoral anatomy, avoidance of the piriformis fossa, and, thus, entry through the greater trochanter, preferably as lateral as possible; (2) smallest practicable proximal footprint to minimize the volume of growth cartilage reamed out at the insertion, thus minimizing the chance of trochanteric growth arrest; (3) adequate proximal bend of the implant to match the curved trajectory of the intertrochanteric region if introduced antegradely; (4) adequate length-to-diameter ratio to ensure that the implant does not bend before fracture healing (Fig. 11.4), although the diameter of the nail cannot mismatch the canal size of the femur excessively; (5) respect for the distal femoral physeal anatomy (it should stop short of the physis and not pass through it except close to skeletal maturity); (6) includes a means of locking the nail at either end (effectively pinning the elastic column), which is essential in length-unstable fractures and to neutralize torsional forces.

Arguments regarding reamed versus unreamed design of the device are secondary to the above principles. Clearly, very-small-diameter nails cannot be made with a hollow core, an advantage that allows introduction of a cannulated intramedullary implant over a guide wire, usually after reaming the canal. As the diameter of the implant increases, then a cannulated design becomes increasingly possible as long as the wall thickness is sufficient to resist failure.

One further theoretical design feature that may have at least short-term advantages is the matching of the modulus of the implant to that of the healing bone. There is a window of ideal stress-strain characteristics of the implant that allows sufficient stimulus of callus by micromotion before hypertrophic nonunion and implant failure supervene. Too much stiffness may result in delayed or atrophic nonunion from stress shielding.

Fig. 11.4 Bent Enders nail

Classification

Location, Comminution, Fracture Orientation

Femoral shaft fractures in children can be classified as open or closed, by location within the bone, degree of comminution, and fracture line orientation. The most commonly used classification for femoral shaft fractures involves a simple anatomical description of the location of the fracture. This system has clinical implications in the decision process for the type of treatment or type of implant used when internal or external fixation is appropriate. Commonly described fracture locations for femoral shaft fractures include proximal one-third (proximal metadiaphyseal), middle one-third (diaphyseal), or distal one-third (distal metadiaphyseal). Each of these fracture locations carries with it its own set of treatment challenges. For example, in proximal one-third fractures, the proximal fragment tends to flex, externally rotate, and abduct from the forces placed upon it by its muscular attachments, while purely diaphyseal fractures tend to angulate into varus and extension from the overpowering forces of the adductors and hamstrings.

Winquist and Hansen classified adult femoral shaft fractures based on the degree of comminution, which remains a descriptive classification in older children [11]. Type I fractures consist of a single fracture line without comminution or very minimal comminution involving only small bony fragments. Type II fractures possess a large cortical fragment that comprise less than 50 % of the circumference of the cortices of the two major fragments. Like type I fractures, these fractures are length stable when reduced and treated with intramedullary fixation. Type III fractures have butterfly fragments between 50 and 100 % of the circumference of the major fracture fragments. This type of injury is not length stable once reduced because the cortical contact between the proximal and distal shaft fragments is limited or absent. Type IV fractures contain segmental comminution. Type III and IV fractures require proximal and distal interlocking screws in the nail to maintain length and stability.

Pediatric femoral shaft fractures also can be classified based on the orientation of the primary fracture line relative to the shaft of the bone. Transverse fracture lines are oriented perpendicular to the long axis of the bone and usually are caused by a higher level of energy trauma than oblique or spiral fractures. Oblique fracture lines are oriented at some angle other than perpendicular to the long axis of the bone and often are described as short or long oblique, based on the length of the fracture line. Spiral fractures travel around the circumference of the bone and usually contain a fracture line that travels parallel to the shaft of the bone, connecting the proximal and distal ends of the spiral fracture line.

Indications and Contraindications of Locked Intramedullary Nailing

Locked intramedullary nailing is the treatment of choice for diaphyseal femoral fractures in adults and should be considered the first-line treatment in adolescents with closed physes. Use of locked intramedullary nails in children and adolescents with open physes, however, remains more controversial. Several authors have demonstrated safe and efficacious use of locked nails in adolescents older than 11 years of age, but concerns about AVN and proximal femoral deformity have led to limited use in children under the age of 11 years [12–15]. Reports of high malunion rates and hardware failures with flexible nails in children who weigh more than 47 kg or who have length-unstable fracture patterns [16] have led some to extend the indications for locked intramedullary nailing to children who meet either of these criteria without reported AVN or proximal femoral deformity [17].

MacNeil et al. performed a recent systematic review of the English medical literature and found no reported cases of AVN using the lateral aspect of the greater trochanter as the entry site [18].

Locked intramedullary nails may be used for simple or comminuted fracture patterns involving any portion of the diaphysis. Most open fractures may be treated with aggressive wound management and acute nailing; however, select type III fractures may benefit from urgent wound debridement and provisional external fixation with delayed intramedullary nailing. Contraindications to locked nailing include previous deformity that will not accept the geometry of the implant, massively contaminated wounds, active infection, and borderline patient parameters including hypothermia, hypovolemia, and coagulopathy [19].

Operative Technique

Preoperative Planning

Before proceeding with intramedullary nailing, careful planning is required. A thorough history and physical examination should be performed, and appropriate imaging should be obtained to include orthogonal images of the entire femur and ipsilateral hip and knee. If the patient meets the appropriate criteria for an antegrade, locked femoral nail, then the canal should be measured to assess if the canal width is large enough to accommodate the available implant. The use of a non-cannulated implant has allowed some manufacturers to produce nails as small as 7 mm in diameter. In most patients, canals can be safely reamed up to 1.0 or 1.5 mm above the size of the implant, or an unreamed nail may be used in some cases. In fractures that have significant comminution, radiographs of the contralateral side may be helpful to assess appropriate length and rotation.

The preoperative condition of the patient also should be considered because many femoral fractures are associated with high-energy mechanisms, resulting in multiple comorbidities. Adequate resuscitation in these patients is necessary to minimize perioperative complications. A basic metabolic panel, hematocrit level, and coagulation panel should be routinely checked. Urine output, lactate levels, and blood gas studies also may be helpful in assessing the level of patient resuscitation. While the timing of intramedullary fixation may be controversial, it usually is preferable to stabilize femoral shaft fractures that can be treated with intramedullary fixation with early total care. External fixation or skeletal traction may be used to temporize treatment in patients with comorbidities that preclude intramedullary fixation.

Technique

After an appropriate preoperative workup has been performed, the patient is taken to the operating room. General anesthesia is induced, often before transfer to the operating table to minimize patient discomfort. Appropriate prophylactic antibiotics are given. The patient is then positioned on a fracture table supine with a well-padded perineal post and well-padded traction boot. The contralateral leg is positioned in a traction boot and scissored down or placed in a well-leg holder. Alternatively, the patient may be placed in the lateral position on a fracture table or on a radiolucent fracture table. Once the patient has been positioned on the table, the operative leg is slightly flexed and adducted, and traction is applied to the leg. Fluoroscopic views are then obtained to ensure that an adequate view of the hip and adequate reduction of the fracture can be obtained. The leg is then prepped and draped in a standard fashion.

A short oblique incision is made approximately 1 cm proximal to the tip of the greater trochanter and extended proximally 2–3 cm. Alternatively, a guidewire can be placed percutaneously into the desired starting point with a small (1 cm) incision around it, allowing passage of a trochanteric reamer. The fascia to the gluteus maximus is incised in line with its fibers. The guidewire is positioned on the lateral aspect of the greater trochanter at least 7 mm, depending on the size of the child (in a smaller child this may be closer) away from the tip of the trochanter (Fig. 11.5a, b). Placement of the guidewire too close to the tip of the trochanter places the course of the reamer close to the piriformis fossa and jeopardizes the blood supply to the femoral head. On a lateral view, the guidewire should be in line with the femoral canal. Care should be taken to avoid errant passes of the guidewire posteriorly or medially to the trochanter to avoid injury to the femoral head blood supply. Once appropriately placed, the guidewire is advanced to the level of the lesser trochanter. The entry reamer or awl is then passed over the guidewire. A soft-tissue guide is used to minimize trauma to the proximal soft tissues. The guidewire and reamer are then removed and, if a cannulated nail is selected, then a reduction tool is passed to the level of the fracture. The fracture is reduced, and the reduction tool is advanced into the distal fragment. A ball-tipped guidewire is then passed into

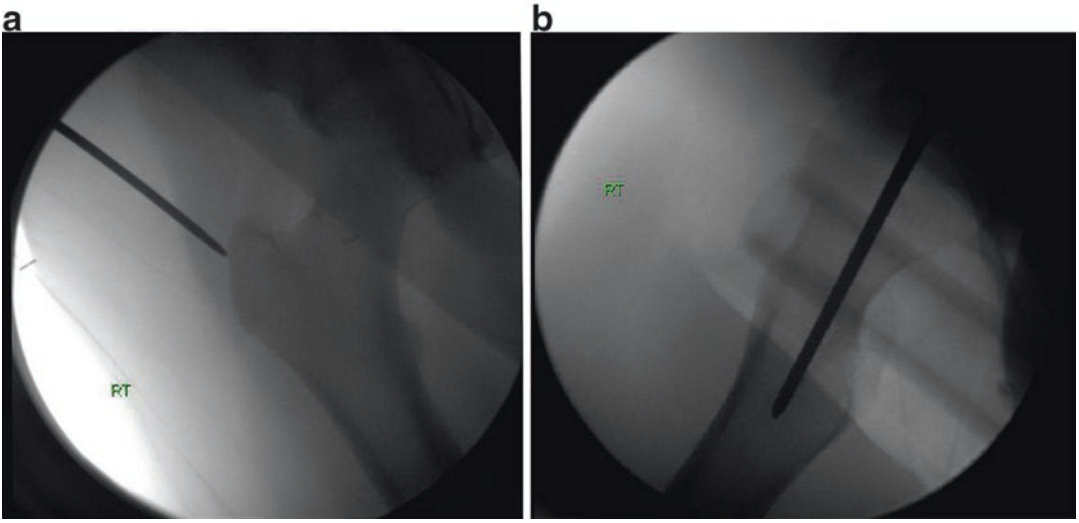

Fig. 11.5 (**a**, **b**) Positioning the guidewire

the distal fragment not farther than 1 cm from the physis or physeal scar. The guidewire should be placed close to the center-center position confirmed by anteroposterior and lateral views. Alternatively, the ball-tipped guidewire can be placed without a reduction tool, but the reduction tool often allows for more accurate placement with fewer attempts. After placement of the guidewire, the reduction tool is removed, and the nail length is measured. If a reamed technique is used, an end-cutting flexible reamer is placed over the guidewire. The canal is then sequentially reamed until there is adequate resistance or until the diameter of the selected implant is exceeded by 1.0 mm. The implant is then assembled to the appropriate outrigger on the back table. If a cannulated implant is selected, the nail is inserted over the guidewire until it is appropriately seated (Fig. 11.6). If a non-cannulated nail or pediatric-specific nail is selected, the guidewire is removed before passage of the implant. For a nonreamed, non-cannulated nail system, a guidewire is not used. The nail is then locked proximally with the use of the guide. The drill sleeve is passed through the guide to mark the level of the skin incision. A 1 cm incision is then made and the soft tissues are spread down to the lateral femur. The drill sleeve is advanced to bone, and a calibrated drill bit is passed bicortically through the proximal interlocking hole in the nail. If the proximal interlocking screw hole is well above the level of the lesser trochanter, a unicortical screw may be placed with purchase in the calcar bone. The screw length is measured, and the appropriate screw is inserted. The screw position is confirmed with the image intensifier. The extremity is then carefully examined with fluoroscopic assistance to ensure that appropriate length and rotation have been restored. Longitudinal traction should be removed before

Fig. 11.6 Screw position confirmed fluoroscopically

distal interlocking. The image intensifier is then positioned at the level of the distal interlocking hole and "perfect circles" are obtained. A 1 cm longitudinal incision is made in the skin centered over the hole, and the soft tissues including iliotibial band are divided. The appropriate drill bit is placed over the center of the hole and then passed through the lateral cortex in line with the fluoroscopic beam. Accurate placement is confirmed before proceeding, and then the drill bit is passed bicortically. The screw length is measured after the drill bit position is confirmed on the anteroposterior view, and the appropriate length screw is placed. A second distal interlocking screw is placed if necessary.

Final imaging is obtained to confirm fracture reduction and implant placement. Additionally, the femoral neck should be reassessed radiographically to ensure that nail insertion has not caused displacement of a previously unrecognized, occult femoral neck fracture. All wounds are then irrigated and closed in standard layered fashion. Prior to waking the patient from anesthesia, the thigh compartments should be evaluated, length and rotation should be compared with the contralateral leg, and the ipsilateral knee should be examined for ligamentous injury.

Postoperative Care

Postoperatively, the patient is admitted for observation and pain control. The patient is mobilized with physical therapy. Range-of-motion exercises and quadriceps exercises should be initiated before discharge. The patient's weight-bearing status is determined by the degree of cortical contact at the fracture site. With satisfactory cortical contact, the patient may be weight bearing as tolerated with an assistive device. If there is comminution at the fracture site or a segmental injury, then the patient should maintain partial or touch-down weight bearing until sufficient callus is noted radiographically. Typically, assistive devices such as crutches or rolling walkers are required for 4–6 weeks. Anticoagulation is not typically required in pediatric or adolescent patients. Nails should not be removed before 9 months from the time of insertion because of the risk of refracture unless otherwise indicated. We routinely remove implants in patients with significant growth remaining.

Risks of Intramedullary Nailing for Pediatric Femoral Shaft Fractures

Pediatric femoral shaft fractures come with a number of risks and potential complications based on the fracture itself, such as compartment syndrome, neurovascular compromise, infection, leg-length discrepancy, angular malunion, rotational deformity, delayed union, nonunion, and muscle weakness. Some of these factors, such as angular malunion and leg-length discrepancy, can be mitigated with the use of solid intramedullary fixation over some other treatment methods. However, intramedullary fixation carries with it a number of additional concerns, including fat embolism syndrome, proximal femoral deformity, and femoral head avascular necrosis.

Malalignment and Malunion

Solid intramedullary fixation can restore length and alignment in the face of a femoral shaft fracture, particularly when the implant is locked using interlocking screws. Open fractures, segmental bone loss, and a high degree of comminution can pose particular challenges for restoring length and alignment. Intramedullary fixation can be helpful in these cases once the wounds are clean and the soft tissues have been managed appropriately to minimize the risk of infection.

Delayed Union and Nonunion

Delayed union and nonunion are both rare in the pediatric population. Most femoral shaft fractures can be expected to unite within a few weeks in infants, 4–6 weeks in children under 5 years of age, and up to 10–14 weeks in adolescents. Open fractures, segmental fractures, or highly comminuted fractures carry the greatest risk for delayed union or nonunion because of the degree of soft-tissue disruption and altered fracture biology. Nevertheless, the osteogenic potential of children typically is enough to overcome even these severe injuries when adequate fracture stabilization is achieved.

As with all fracture nonunions, the patient should be evaluated for infection with appropriate laboratory studies and possibly culture of the nonunion site. If infection is discovered, debridement of the nonunion site is required along with appropriate antibiotic treatment. If infection is ruled out, solid intramedullary fixation is an excellent option for pediatric femoral shaft nonunions when other treatment, such as casting alone or external fixation, was previously used. Exchange femoral nailing can also be helpful when a nail was previously used. Simply removing the nail, reaming the canal, and implanting a larger interlocked nail can be enough to lead to union in many cases (Fig. 11.7a–c).

Dynamization of a previously interlocked nail might be helpful in some hypertrophic delayed unions, particularly when a gap is seen at the fracture site. However, little information is available on the use of this practice in the pediatric population, and dynamization has largely been abandoned in the treatment of adult nonunions.

Femoral shaft atrophic nonunions are exceedingly rare in children; they typically occur in the case of severe soft-tissue damage or large amounts of periosteal stripping such as from high-energy gunshot wounds or severely contaminated open fractures (Fig. 11.8a–d). In atrophic nonunions, simply stabilizing the fracture with an intramedullary implant or plate fixation will not be enough to ensure bony union. These injuries require improvements in the local biology in addition to improvements in fracture stabilization. Local fracture biology can be improved with rotational muscle flap coverage, autologous bone grafting, and perhaps bone morphogenic protein.

Nonsteroidal anti-inflammatory drugs (NSAIDs) are excellent adjuncts to narcotic pain medication in the treatment of fracture-related pain in children. However, there is a concern that NSAID use can delay fracture healing or lead to nonunion [20]. This concern has not been substantiated in children; nevertheless, NSAIDs should be prescribed judiciously in children with a higher risk of delayed union or nonunion.

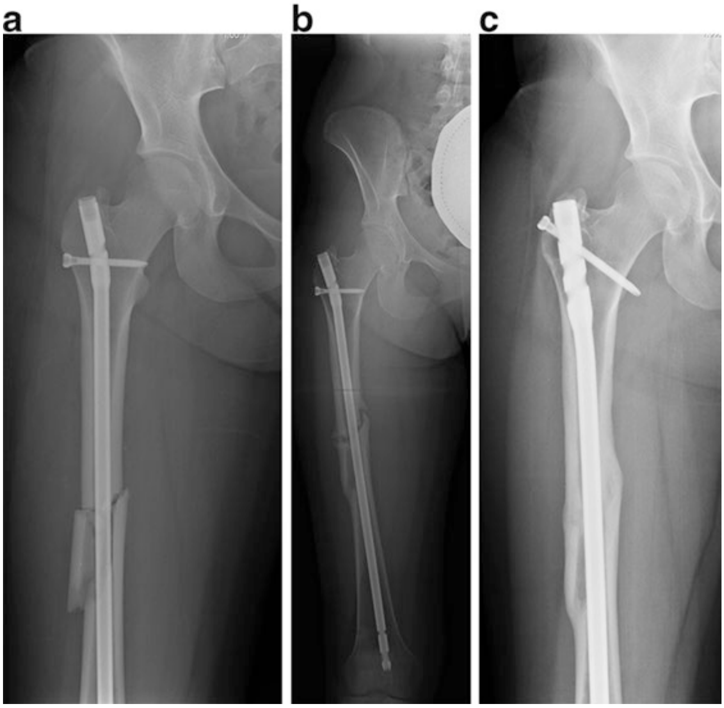

Fig. 11.7 (**a**–**c**) Exchange femoral nailing in nonunion. (**a**) Nonunion of femoral shaft fracture. (**b**) Postoperative radiograph of exchanged nail. (**c**) Healed fracture

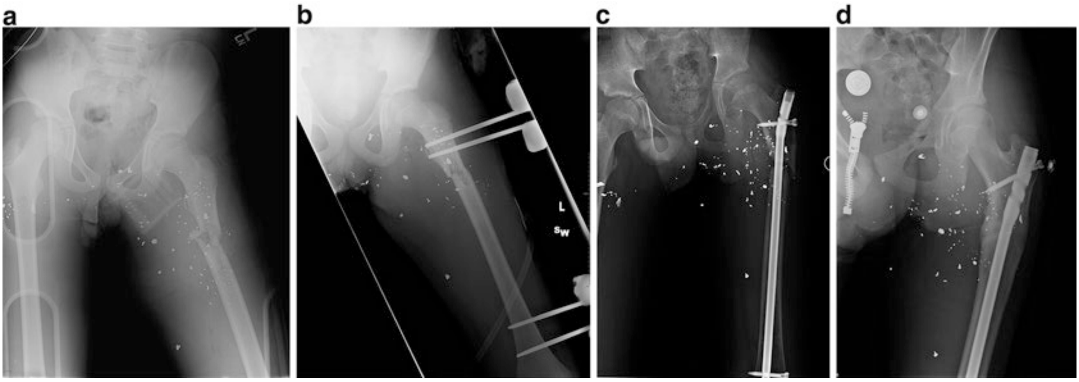

Fig. 11.8 (**a**) Proximal femoral shaft fractured caused by gunshot. (**b**) Treated with external fixation. (**c**) Nonunion developed, and the patient was treated with intramedullary nailing. (**d**) Radiograph reveals fracture healing

Fat Embolism Syndrome

Fat embolism syndrome is extremely rare after femoral shaft fractures in children. Fat embolism syndrome has both mechanical and biochemical effects on the vascular system. The fat globules can occlude small vessels, causing localized ischemia. Also, fatty acid release can cause endothelial damage that is aggravated by platelet and granulocyte activation. It can also cause pulmonary symptoms such as hypoxemia and shortness of breath. Neurologic symptoms include agitation, delirium, and coma. Anemia and thrombocytopenia can develop. A petechial rash is pathognomonic, but it only develops in less than 50 % of patients [21].

In a review of 42 ipsilateral femoral and tibial fractures, the authors only had one patient with symptoms of fat embolism syndrome [22]. It is unclear if the intramedullary contents of the femoral fracture were responsible for the symptoms. Most studies of fat embolism syndrome after long-bone fractures demonstrate a reduction in the incidence with early operative stabilization of the fractures [23]. However, there was one report of fat embolism syndrome developing after closed femoral shortening over a nail in two patients under the age of 18, suggesting that the placement of the intramedullary device may contribute to the development of fat embolism syndrome [24]. The authors recommended postoperative pulse oximeter monitoring in these patients.

Infection

Infection after intramedullary treatment of closed femoral fractures in children is exceedingly rare. The exact cause of such infections is difficult to determine and is likely related to iatrogenic introduction of a pathogen during the operative procedure, or hematogenous seeding of the surrounding fracture hematoma. In either case, persistent fever longer than 1 week from the time of treatment along with worsening pain, thigh swelling, or redness should raise concern for possible infection.

Infection after open fractures of the femur is much more common. One series reported a 50 % femoral osteomyelitis rate after grade III open fractures [25]. A combination of severe soft-tissue trauma and a large degree of wound contamination in these injuries is likely to blame.

Another potential source of deep infection after intramedullary stabilization in children occurs in the setting of temporary external fixation or distal femoral skeletal traction used to initially treat a patient who might be too unstable upon initial presentation to undergo definitive treatment with an intramedullary device. Letts et al. reported one case of osteomyelitis in 54 patients after intramedullary nail placement for pediatric femoral shaft fractures. This case occurred in a child treated with an intramedullary nail after a period of external fixation [26].

Muscle Weakness

Muscle weakness after femoral fracture has been reported in the quadriceps, hamstrings, and hip abductors. Single-leg hop may diminish relative to the contralateral uninjured extremity [27]. Thigh atrophy of up to 1 cm was present in almost half of the patients in the same series. Others have demonstrated quadriceps and hamstring weakness after nailing and plating of femoral fractures [28]. Weakness of the hamstring and quadriceps also has been demonstrated in fractures treated with or without surgery [29]. It has been postulated that most of the muscle weakness after femoral fracture results from localized muscle scarring, and is related to the severity of soft-tissue injury and degree of femoral shortening at the time of fracture. However, abductor weakness after antegrade intramedullary nailing is iatrogenic, and results from damage to the muscles during nail insertion or localized abductor heterotopic ossification [30].

Proximal Femoral Deformity and Greater Trochanteric Growth Arrest

Early reports on the use of intramedullary fixation for femoral shaft fractures in children discussed the development of proximal femoral deformities such as femoral neck narrowing, coxa valga, and greater trochanteric growth arrest [6, 7]. These earlier studies focused more on the radiographic findings than on functional deficits. Most of these deformities developed in children younger than 13 years, and in children in whom the piriformis entry site was used, indicating that these proximal femoral deformities were most likely related to alteration in growth of the proximal femur. Because of concerns over femoral head avascular necrosis and proximal femoral deformity with piriformis-entry nailing in children, nail designs changed to allow antegrade nailing through a trochanteric entry. The published studies on proximal femoral growth disturbance after this transition in nail entry point revealed much lower rates of clinically significant proximal femoral deformity [14, 31, 32]. Momberger et al. reported a 5-year follow-up in 48 patients [31]. Although they reported a slightly increased articulotrochanteric distance compared with the uninjured contralateral side, they noted no other significant proximal femoral deformities [31]. Gordon et al. had similar findings in 25 patients in a 2-year follow-up study; they found no clinically significant femoral neck valgus, femoral neck narrowing, or trochanteric shortening with the use of lateral transtrochanteric entry [32]. Keeler et al. confirmed these findings with an 8-year review of 78 children treated with trochanteric entry femoral nail for femoral shaft fracture. They found no evidence of valgus of the proximal femur or femoral neck narrowing [14].

Femoral Head AVN

Possibly the most feared complication after femoral nailing of pediatric femoral shaft fractures is femoral head avascular necrosis, or AVN. This complication has a long history within the pediatric orthopedic literature, and the prevention of this complication has led to significant changes in implant design and operative technique.

The blood supply to the growing femoral head has been well described [33]. The main arterial supply comes from the ascending branch of the medial femoral circumflex artery (see Fig. 11.2). This vessel traverses the region of the piriformis fossa, making it vulnerable to trauma to that area such as occurs with femoral neck fractures. That vessel also is at risk with insertion of antegrade intramedullary implants that use a piriformis fossa entry site. Early nail designs took advantage of this location for implant insertion because it allowed for the utilization of a straight nail, as the piriformis fossa is more in line with the intramedullary canal of the femur.

Early reports of piriformis entry nailing for pediatric femoral shaft fractures demonstrated some cases of proximal femoral deformity and greater trochanteric arrest, but no cases of AVN [34]. However, by the mid-1990s published accounts of femoral head AVN began to appear. Beaty et al. reported one patient with asymptomatic AVN in 31 adolescent femoral shaft fractures treated with interlocking nails (Fig. 11.9) [4]. The following article in that same journal issue by Galpin et al. reported 37 femoral shaft fractures but no cases of AVN [35].

Throughout the mid- to late 1990s, multiple case reports were published describing femoral head AVN after antegrade intramedullary nailing entering through the piriformis fossa [36–38]. In some cases, the authors concluded that the risk of AVN was too high, and the resultant outcome too devastating, to consider piriformis entry nailing safe in the adolescent population. Others thought that the rate of AVN was quite low and often asymptomatic, and that the practice could be considered a safe and effective procedure [39].

Nevertheless, by the late 1990s most pediatric rigid intramedullary devices had transitioned away from the piriformis fossa entry point and to the tip of the greater trochanteric, and then to the lateral aspect of the greater trochanter. As the use of these devices became more popular through the late 1990s and early 2000s, publications touting their safety emerged (Table 11.1).

Fig. 11.9 Avascular necrosis of the femoral head following piriformis entry

MacNeil et al. published a systematic review of the literature on femoral head avascular necrosis after intramedullary nailing of femoral shaft fractures in children [17]. From a total of 1277 possible articles, they found 19 that met their inclusion criteria. From this group of articles, they compiled a 2 % rate of AVN with piriformis entry nailing, a 1.4 % incidence with greater trochanteric entry, and a 0 % risk with entry into the lateral aspect of the greater trochanter. They concluded that the lateral aspect of the greater trochanter was the safest entry point for antegrade nailing of pediatric femoral fractures [18].

The avoidance of femoral head AVN with greater trochanteric entry femoral nailing has led to a resurgence in the use of these devices in younger and younger age groups. Recently, Miller et al. [17] published a report on the use of these devices in a group of 17 children under the age of 12 years, with no cases of AVN. Their indications were length-unstable fracture patterns and fracture in obese children. In both situations, they thought that flexible intramedullary implants would have been unreliable at maintaining fracture alignment.

Implant Removal Considerations and Periprosthetic Fractures

The scientific literature provides little guidance to the surgeon as it relates to the decision for femoral nail removal after fracture healing in children. There are studies on implant removal, implant retention, and periprosthetic fracture in

Table 11.1 Publications on safety of rigid intramedullary nailing

Publication	No. of patients	Nail entry	Follow-up	No. of patients with AVN and/or deformity
Momberger et al. [31]	48	Greater trochanter	5 years	None
Townsend and Hoffinger [40]	34	Trochanteric tip	–	None
Kanellopoulos et al. [41]	20	Trochanteric	29 months	None
Keeler et al. [14]	80	Lateral entry	99 weeks	None
Miller et al. [17]	18	Antegrade trochanteric	2 years	None

the young patient, but most focus on metalwork other than solid intramedullary nails. The current body of knowledge on this topic is fairly evenly divided between articles supporting routine implant removal and those opposing it.

Two expert opinion papers recommended routine implant removal in certain cases [42]. Peterson suggested removal of all Kirschner wires and Steinmann pins, all hip blade plates, all lower extremity long-bone plates, and all metallic implants in patients wishing to participate in contact sports [42]. He pointed out that these recommendations are based on experience and literature review; the lack of scientific substantiation may provide a basis for discussion [42]. Kanilik and Cruz recommended routine nail removal in children to prevent periprosthetic fractures, but provided no data on the risk of such an injury [43].

The potential benefits of routine implant removal are the prevention of periprosthetic fracture, improvement in pain and outcome scores, and ease of total hip arthroplasty if required later in life. In each of the studies touting the benefits of routine removal of implants in children, only one study speaks directly to the removal of solid femoral nails [4].

In one of the first articles describing femoral head AVN after piriformis entry nail, Beaty et al. reported the routine removal of all the nails in their study population with no incidence of post-removal femoral neck fracture at 14-month follow-up [4]. Another study reported 25 implant-related fractures in children, but all were associated with plates rather than nails [44].

Chu et al. attempted to study the pain and functional outcome of children undergoing routine implant removal. They obtained Pediatric Outcomes Data Collection Instrument (PODCI) and pain scale data before and after implant removal in 25 children. PODCI was normal before removal and only improved in patients with pre-removal pain or in those who had implants removed from the upper extremity [45]. In one study, implants were routinely removed in 300 patients (average age 11 years) [46]. The authors concluded that, when performed, routine implant removal was easier when performed early rather than late [46].

In a review of over 15,000 total hip arthroplasties at the Mayo Clinic, 31 patients required removal of pediatric implant at the time of total hip arthroplasty. Patients who required implant removal had longer surgery, more blood loss, and longer hospitalizations. The authors recommended routine removal of all proximal femoral implants in pediatric patients likely to require total hip arthroplasty later in life [47]. When polled, pediatric and nonpediatric orthopedists collectively recommended routine removal of pediatric implants 41 % of the time. The pediatric orthopedic specialists only differed from adult orthopedic specialist colleagues in regard to implants placed near the hip. The nonpediatric orthopedists preferred routine removal of this hip implant more often than did the pediatric orthopedists, suggesting that removal of those implants when performing procedures such as total hip arthroplasty later in life is a challenge [48].

The risks of implant removal include exposure to additional anesthesia, postoperative complications such as infection, post-implant removal fracture, and retained implant despite attempted removal. Again, most of the studies listing the potential downsides of implant removal focus on implants other than solid femoral nails. The fairly high rate of complications and sparse literature describing the risks of implant retention have led many authors to question routine removal of pediatric implants.

Complications after implant removal in children have been reported to be as high as 13 % [49]. Complication rates after implant removal are higher in children who had complications after implant insertion, children in whom implants were removed for a nonelective indication, children with neuromuscular disease and associated seizure disorder or the inability to walk, and children with a diagnosis of slipped capital femoral epiphysis [50, 51]. A systematic literature review for implant removal in children listed an overall complication rate of 10 %. This review only looked at the rate of complications for implant removal and did not compare these rates with implant retention [51].

The rate of fracture after plate removal for varus derotational osteotomy has been reported to be 5 % after removal of plate in Perthes disease. Fracture was more common if the plates were removed sooner than 6 months after insertion [52]. Refracture after implant removal has also been reported for flexible intramedullary nail removal [53].

Unsuccessful implant removal or incomplete implant removal also occurs. Incomplete removal of implants has been reported to be as high as 7 % for a mixed group of pediatric implants. Flexible nail retention despite attempted removal has also been reported [53].

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Physeal, Epiphyseal, and Intra-articular Fractures of the Distal Femur

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Introduction and Epidemiology

Distal femur fractures that do not involve the diaphysis can generally be divided into three categories, consisting of (1) those that involve the distal femoral physis, either with (i.e., Salter-Harris II) or without (i.e., Salter-Harris I) extension into the metaphysis; (2) physeal fractures that extend into the epiphysis (Salter-Harris III or IV); and (3) those that are limited to the epiphyseal region, which generally consist of lateral femoral condylar osteochondral shear fractures following lateral patellar dislocation.

Distal femoral physeal fractures are relatively rare, representing approximately 2 % of all physeal fractures [1–3], but have a relatively high complication rate, the most common of which is growth disturbance due to partial or complete premature physeal closure (i.e., bony "bar" formation). Such sequelae, which may occur in up to half of cases [4], make close monitoring of these fractures in the post-injury or postoperative period through skeletal maturity critical to avoid clinically significant angular deformities or leg length discrepancies. Due to the high energy required to cause these fractures, displacement and instability are common, and in general, nonoperative treatment is pursued less commonly than fixation, the principles of which are described in a below section. Adolescents and preadolescents are the most affected age group for distal femoral physeal injuries [5], in part because of increases in sports participation and sports-related injuries, which represents a common mechanism of injury for these fractures.

The treatment of Salter-Harris III or IV fractures of the distal femur, or osteochondral fractures that involve significant portions of the weight-bearing zones of the articular surface, should consist of anatomic reduction and fixation so as to optimize the long-term outcome and avoid degenerative joint disease. While Salter-Harris III or IV fractures are relatively rare, the prevalence of osteochondral fractures associated with acute patella dislocation ranges from 19 to 50 % [6–8]. Osteochondral fracture fragments may range from small incidental loose bodies to large portions of the articular surface. While osteochondral fractures occur in the patella even more commonly than the lateral femoral condyle, the treatment of patellar lesions is beyond the scope of this chapter, so the focus will be on treatment of condylar fractures, the principles of which are nearly identical to those of the patella. Treatment of intra-articular osteochondral fractures generally involves an initial arthroscopy and includes

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removal of small loose bodies, but fixation for larger osteochondral fragments. The underlying or resulting patellar instability is sometimes addressed with concurrent stabilization surgery, in the form of medial retinacular repair or reefing, medial patellofemoral ligament (MPFL) reconstruction, lateral retinacular release, and/or distal realignment techniques, such as tibial tubercle osteotomy for skeletally mature adolescents, and soft-tissue tendon transfers in the skeletally immature.

Mechanism of Injury

Fractures of the distal femoral physis are often high-energy injuries, such as from motor vehicle accidents, sports-related injuries, or, occasionally, falls from height. Fracture patterns relate to the underlying anatomical changes of the growing child. The collateral ligaments and their bony attachments in an adolescent or a child are actually relatively stronger than the cartilaginous growth plate. Therefore, the classically described mechanisms that lead to high-grade medial collateral ligament (MCL) or lateral collateral ligament (LCL)/posterolateral corner (PLC) tears in an adult—lateral or medial direct blows to the knee, respectively, with a planted/fixed foot—will instead cause a distal femur Salter-Harris fracture in a skeletally immature patient. Hyperflexion or hyperextension injuries can lead to fracture patterns with displacement in the sagittal plane.

Distal femoral osteochondral fractures, on the other hand, stem from either a direct blow to the knee with a shearing force applied to either the medial or lateral femoral condyle (LFC) or more commonly a flexion-rotation injury in which internal rotation at the knee is paired with a strong quadriceps contraction. When the patella dislocates in this scenario, the medial edge of the patella impacts the prominent edge of the LFC before it slides back into the trochlear groove due to pull of the quadriceps. Either the dislocation or the relocation phase of this injury can cause an osteochondral fracture to the LFC, the medial facet of the patella, or both.

Other mechanisms of injury are less common. Newborns can sustain distal femoral physeal fractures from birth trauma, with identified risk factors including prolonged labor, macrosomia, and breech presentation [9]. Child abuse, sometimes identified through the presence of a subtle metaphyseal fragment or “corner fracture,” most commonly occurs in infants and toddlers [10]. As with all types of fractures, pathologic fractures can occur with lower energy mechanisms due to underlying metabolic bone disease or osteopenia, and nonambulatory patients with cerebral palsy and other neuromuscular disorders may sustain distal femoral physeal injuries from falls or direct blows.

Evaluation and Diagnosis

Presentation and Physical Examination

Due to the high-energy mechanisms that often cause distal femur physeal fractures, awareness of concomitant fractures and other injuries is essential in the initial evaluation. A thorough secondary survey should be performed, particularly in the setting of a motor vehicle accident or a fall from height. In approximately 10–15 % of cases of distal femur fractures [11, 12], other long bone fractures or ligamentous disruptions about the knee will be present, such as cruciate ligament tears. A standard orthopedic trauma workup, including assessment of the spine and pelvis and neurovascular assessment of the involved distal extremities, should be performed. While open fractures and major arterial injuries are rare, occurring in 3 % of cases, the initial evaluator should carry a low threshold to perform Doppler ultrasound and/or assess ankle-brachial indices (ABI), particularly with severely displaced fractures or following severe hyperextension knee injuries. Compartment syndrome following distal femoral fractures is rare, occurring in 1.2 % of cases in one series [11], and will typically arise in the hours or day after the initial injury. The peroneal nerve may be injured in up to 7 % of displaced distal femoral fractures [11]. Concomitant injuries are rare with patellar dislocations, though ligament tears (other than MPFL tears, which are an inherent component of virtually every patellar dislocation, to varying degrees), such as MCL and anterior cruciate ligament (ACL) ruptures, can occur. Most cases of distal femoral physeal injuries or patellar dislocations occur in isolation, however, particularly when presenting as sports injuries.

Children with distal femur fractures will usually refuse to bear weight, and deformity may be obvious, even before radiographs are obtained. Swelling and ecchymosis are often present about the knee, and severe effusions are common, particularly with Salter-Harris III or IV fractures and osteochondral shear fractures of the condyles. Lower energy Salter-Harris I or II fractures can be more subtle, however, with children able to bear weight, albeit with discomfort, and differentiation from other knee injuries, such as meniscal or ligament injuries, is important. Varus and valgus stress exams should be performed, which may show instability due to the compromised distal femoral physis. Lateral or medial tenderness in the region of the distal femoral physis may also direct the diagnosis. A stable knee with tenderness to palpation over the medial patella, medial epicondylar region (Bassett's sign), and lateral aspect of the lateral femoral condyle are most common in association with lateral patellar dislocation. Late exam findings in such cases may reveal signs of a loose body, with locking or catching of the knee. Early splinting with long leg plaster splints or knee immobilizers is warranted for early stabilization and to improve comfort.

A thorough imaging assessment, with plain radiographs and possibly computed tomography (CT) and/or magnetic resonance imaging (MRI), is the next step in the diagnostic workup, once concurrent limb-threatening injuries have been ruled out and the affected lower extremity stabilized.

Diagnostic Imaging and Classification

Anteroposterior (AP) and lateral femur radiographs should be obtained in all cases of suspected distal femur fractures. Radiographic assessment of the proximal femur and femoral head is critical, particularly for high-energy injuries, as concomitant femoral neck fractures can occur with femoral shaft and distal femoral fractures, and failing to diagnose such fractures, even when non-displaced, can have catastrophic sequelae. When the injury is localized to the knee, dedicated AP and lateral knee radiographs should be obtained, with lateral and medial oblique knee radiographs added at times to better elucidate subtle fractures or in the face of diagnostic uncertainty. Dedicated tibia/fibula radiographs may be warranted at times, especially in patients with concurrent leg or ankle complaints.

Findings typical of the radiographs in a distal femoral physeal fracture include physeal widening that may be seen in isolation (suggesting a Salter-Harris I fracture), or in association with extension of the fracture line into the metaphysis (Salter-Harris II), epiphysis (Salter-Harris III), or both metaphysis and epiphysis (Salter-Harris IV). Salter-Harris V fractures, which represent an axial compression phenomenon on the distal femoral physis, or Salter-Harris VI fractures [13, 14], in which a collateral ligament avulses a condylar fragment of bone containing a segment of peripheral physis, have been described but are rare. SH-V injuries have been described most commonly following a fall from height and will generally have negative radiographs, but may be picked up on MRI, due to the presence of bone marrow edema on one or both sides of the physis [15]. These have a high rate of premature closure of the physis. Interestingly, in most anatomic locations, the Salter-Harris system is fairly predictive of rates of premature physeal closure, with the higher grades (SH-III and SH-IV) having higher rates of closure. However, the distal femoral physis is particularly sensitive to even minor disruptions, with all Salter-Harris types having high rates of premature physeal closure, which has been described even in tibial shaft injuries [15–18]. In these cases, occult SH-V injuries to the distal femoral physis may have been present.

For a possible osteochondral fracture of the condyle, a skyline plain radiograph should be added to the knee series, though patients may not be able to achieve the degree of knee flexion necessary for this view. Because osteochondral fragments may involve large portions of cartilage with only a sliver of bone, radiographs should be carefully assessed for even the smallest ossific fragment. One study suggested that radiographs *failed* to identify osteochondral fracture in 36 % of children who had such injuries found during arthroscopy [19]. MRI should therefore be considered in all cases of lateral patellar dislocation with an associated effusion. For suspected distal femoral physeal fractures not clearly identifiable with radiographs, MRI can show a subperiosteal hematoma about the physis and adjacent metaphysis, though comparison radiographs of the contralateral knee may also allow for elucidation of subtle physeal widening characteristic of Salter-Harris I fractures. One series reported seven cases of such fractures clearly seen on MRI, but with negative radiographs [20].

While "stress views" of the knee or distal femur were historically recommended to identify non-displaced Salter-Harris I or II fractures, this approach is rarely used today, given the pain and potential fracture displacement associated with the involved varus or valgus stress maneuver, and the greater availability of advanced imaging modalities. Modern CT scan sequences have been developed to decrease the amount of radiation used in children compared to historical techniques, and can be obtained more quickly than MRI. Because decisions regarding surgical stabilization often relate to the degree of displacement or stepoff across an articular surface, a CT scan may be indicated for Salter-Harris III or IV fractures, or osteochondral fractures about the knee [21, 22].

The role of ultrasonography (US) is limited to physeal fractures in infants and newborns, but may help assess displacement of a distal femoral fracture in which there is minimal developmental ossification [23].

Treatment Options and Outcomes

Nonoperative Treatment: Salter-Harris I and II Fractures

Non-displaced or minimally displaced Salter-Harris I or II distal femoral physeal fractures may be treated with long leg casts or even long leg braces, such as locked hinged braces or knee immobilizers, provided that they are utilized like casts. However, casting is generally more likely to optimize stability of the healing fracture in the first 2 weeks post-injury and thereby minimize discomfort. Moreover, a circumferential fiberglass cast, with or without inclusion of the foot, eliminates concerns related to noncompliance with brace wear, which can be an issue in the pediatric and adolescent patient populations. Because some of these fractures are relatively stable, transitioning after 2–4 weeks from a cast to hinged brace—which can be unlocked when not ambulating to work on range of motion, thereby helping to combat stiffness and deconditioning of the periarticular musculature—can be considered if there is a truly stable pattern and/or early signs of healing are present.

It is important to remember that more displacement may have occurred at the time of injury than the presenting radiographs demonstrate, and that severe soft-tissue swelling and ecchymosis may be an indication of an unstable fracture, which should prompt consideration of fixation to optimize stability and healing. One study demonstrated that over one-third of a series of 82 patients with distal femoral physeal fractures treated with closed reduction and casting progressed to redisplacement in the first 2 weeks, only one-quarter of which were to be remanipulated later [11, 12]. This and other studies underscore the dangers of pursuing less treatment than may be necessary, given the considerable energy associated with femur fracture injuries. For the truly stable fractures, however, serial radiographs, which may demonstrate subperiosteal and/or periphyseal new bone formation, will inform considerations of transitioning from casting to bracing.

Salter-Harris III and IV Fractures

Salter-Harris III and IV fractures of the distal femur are rarely non-displaced enough to warrant nonoperative treatment. Because radiographs may not show subtle degrees of subchondral

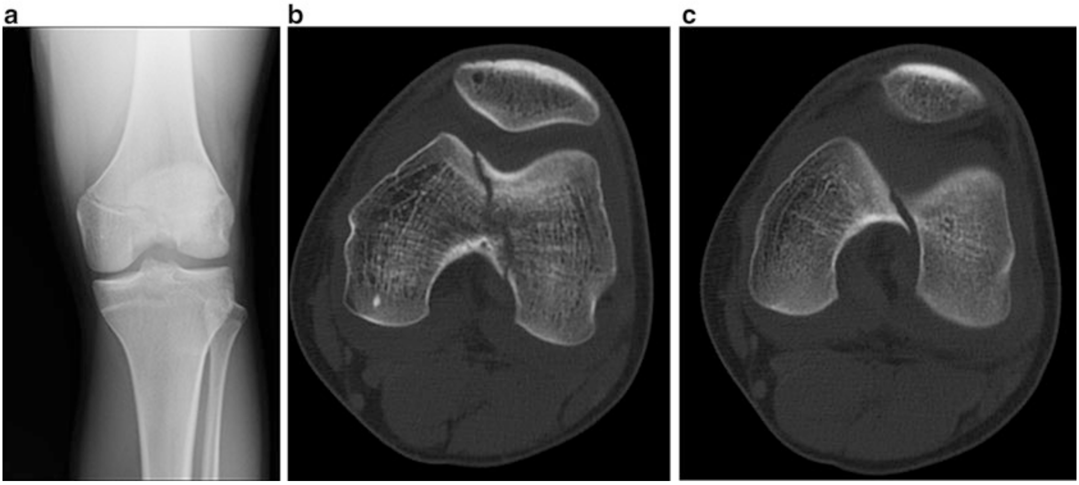

Fig. 12.1 (**a**) Radiograph suggesting non-displaced Salter-Harris III fracture in a 17-year-old hockey player following a moderate-energy leg-to-leg blow. (**b**, **c**) CT scan of the same patient in (**a**) showing 2 mm stepoff in the central weight-bearing zone of the medial trochlear ridge extending into the notch

stepoff that could have significant long-term implications on the development of degenerative joint disease, advanced imaging should be obtained before management decisions concluded (Fig. 12.1a–c). Even for minimally displaced fractures, there may be a role for minor reductions and stabilization to insure maintenance of anatomic subchondral surfaces with minimal stepoff at the level of the articular cartilage. Moreover, the earlier range-of-motion exercises allowed by such stabilization have been shown to be beneficial for healing cartilage and preventing stiffness.

Intra-articular Osteochondral Fractures

Nonoperative treatment of intra-articular condylar osteochondral fractures associated with patellar dislocation is reserved only for small fragments, 5–8 mm or less, that are unlikely to cause symptoms associated with loose body fragments. Occasionally, larger fragments will adhere to the soft tissues in a non-weight-bearing region of the joint, such as the medial or lateral gutter or the posterior intercondylar notch. In such cases, particularly when presenting in delayed fashion (>2–4 weeks), non-operative management can be considered, but the risk of future displacement with intra-articular injury to the joint surfaces by the fragment should be discussed with the patient and family.

Operative Treatment: Salter-Harris I and II Fractures

Displaced distal femoral physeal fractures warrant restoration of the physeal anatomy, periphyseal alignment, and a form of stabilization that respects the presence of the still biologically active physis, the normal future function of which is in question with all distal femoral fractures. While fracture tables involving traction constructs may be reasonable, they are usually not necessary, and a simple radiolucent table is favored by most authors. The first step for displaced fractures is achieving a perfect reduction, which should be performed under general anesthesia or adequate intravenous sedation to minimize further shear forces across the chondral tissue of the physis. Understanding of the fracture pattern and which sleeve of periosteum about the physis remains intact and can be utilized as a tether to achieve the reduction is critical. For example, a Salter-Harris II fracture sustained by a direct valgus blow to the lateral aspect of the knee will generally have an intact lateral periosteum against which varus stresses can be applied to achieve anatomic approximation of the medial physis.

While closed techniques are usually sufficient to obtain an anatomic reduction, if one cannot be obtained, an open incision on the side that the fracture originated (most commonly, the medial physis for Salter-Harris II fractures) should be made to assess for periosteal interposition and optimization of the physeal approximation. Following anatomic reduction, choice of fixation depends on the fracture pattern. For Salter-Harris II fractures that have an adequately sized Thurston-Holland fragment to accommodate one to three large screws (6.5 or 7.3 mm), good stability can be achieved with cannulated, partially threaded screws placed parallel and just proximal to the physis from the fragment side to the unfractured metaphyseal side. Generally, washers on the fracture fragment side are also advisable to prevent breakthrough of the screw head through the relatively thin metaphyseal cortical bone during compression. However, when multiple screws are placed on relatively smaller metaphyseal fragments, it is not uncommon to have insufficient room for multiple washers, in which case a single washer can be used to achieve compression and optimize the reduction, while additional screws reinforce the construct without washers. Smaller sized screws, such as one or two 4.5 mm screws, can also complement a single larger screw that achieves the reduction. Bicortical purchase may be pursued, but given the large size of the screws, it is often not necessary, and care should be taken to prevent screw tip protrusion beyond 1–2 mm. Because most Salter-Harris II fractures have a lateral metaphyseal fragment, medial soft-tissue irritation just above the epicondyle is not an uncommon complaint when the screw tips are placed beyond the cortex. The best way to appreciate the exact position of the screw tips is to use live fluoroscopy while rotating the knee at least 30° in either direction from the anteroposterior plane. Removal of hardware is not necessary in most cases, but in children with significant growth remaining the screws often "migrate" proximally toward the diaphyseal segment over time, making any extruded screw tips longer relative to the metaphysis. Some authors favor empiric screw removal, but this remains an evolving concept within all of pediatric orthopedic surgery.

For Salter-Harris I fractures or S-H II fractures with metaphyseal fragments too small to safely accommodate a screw, transphyseal smooth k-wires are placed in a crossed, X-shaped construct to optimize stability. Authors have described pin sizes between 2.4 and 3.2 mm. These can be placed in anterograde fashion from metaphysis to epiphysis, with the pin tips advanced to just short of the subchondral bone, or in retrograde fashion from epiphysis to metaphysis [24]. With this latter approach, care is taken to place the epiphyseal entry point at least 1–2 mm off of the articular surface to avoid chondral injury. However, because this approach necessarily leaves segments of the hardware within the knee joint, two strategies are pursued to avoid bacterial seeding of the intra-articular k-wires and minimize the risk of septic arthritis. One technique is advancing the k-wires all the way out of the skin proximally in the thigh, and pulling the k-wires further proximally, so that the trailing tip of the pin sits in the subchondral bone and the leading tip is cut and bent at the level of the skin of the thigh, to be removed manually weeks later in the office setting [25]. The second technique is placing the trailing tip of the retrograde-placed k-wire deep to the skin, thereby protected from external microbes and bacterial skin flora that would otherwise potentially migrate down the pin into the joint, with a plan to remove the wires with a secondary surgery after sufficient healing has been achieved. Due to several studies demonstrating cases of septic arthritis, leaving retrograde-placed pins out of the skin at the level of the knee is no longer routinely favored.

Rarely, plating of distal femoral physeal fractures is pursued, with the plate spanning the physis, screws placed parallel to the physis, proximal and distal, and optimal stability achieved. While this technique has the distinct disadvantage of larger incisions, even when minimally invasive submuscular plating techniques with percutaneous proximal screw placement are used, good outcomes have been reported in one series [25].

Salter-Harris III and IV Fractures

Salter-Harris III and IV fractures warrant anatomic reduction and stable fixation. Occasionally this can be achieved without performing an arthrotomy, which may decrease the chances of knee stiffness that comes with the extra dissection and disruption of the joint capsule. However, due to the importance of optimally restoring articular congruity in a young, active patient, surgeons should have a low threshold to open the joint (Fig. 12.2) or use arthroscopy (Fig. 12.3a–c) to confirm an anatomic reduction. Moreover, radiographs should show normal physeal thickness at all levels, and similar to Salter-Harris II fractures, periosteal interposition should not be overlooked as a potential block to an anatomic reduction [26]. Screw constructs and directionality vary according to the fracture pattern, but in skeletally immature patients, screws must often be placed very exactly, just below the physis, but just above the roof of the intercondylar notch to avoid iatrogenic cruciate ligament injury (Fig. 12.4a–d). However, in patients with closing growth plates, screw constructs may cross the growth plates to optimize the reduction and fixation construct (Fig. 12.5a–c).

Intra-articular Osteochondral Fractures

Large osteochondral fragments of the lateral femoral condyle, 1 cm and above, warrant operative treatment. Generally these contain cartilage that is

Fig. 12.2 Arthrotomy for displaced Salter-Harris III fracture sustained by a 15-year-old skeletally immature football player during a violent leg tackle

Fig. 12.3 (**a**) Fluoroscopic image of the same patient from Fig. 12.1 demonstrating arthroscopic assistance of reduction. (**b**) Arthroscopy image of the same patient from Fig. 12.1 demonstrating minimal persistent displacement following reduction of stepoff and provision wire fixation. (**c**) Arthroscopy image of the same patient from Fig. 12.1 demonstrating optimization of the trochlear articular surface, with no stepoff and no displacement following compression screw fixation

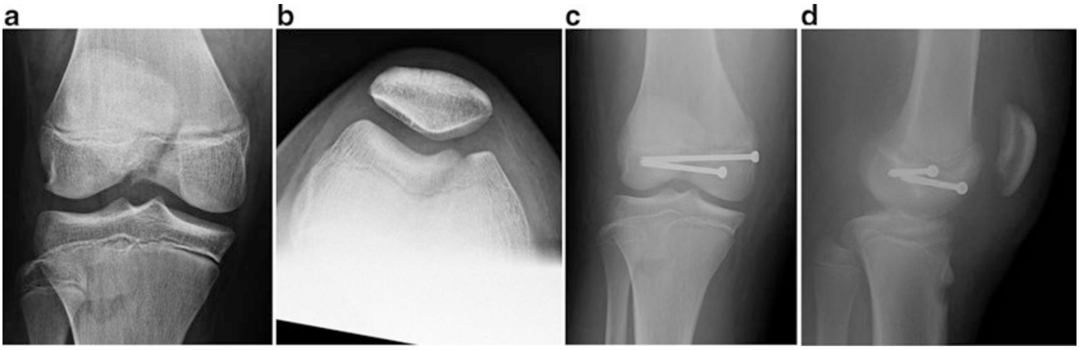

Fig. 12.4 (**a–d**) AP and lateral radiograph images from the same patient as in Fig. 12.2 demonstrating screw fixation just distal to physis and proximal to intercondylar notch

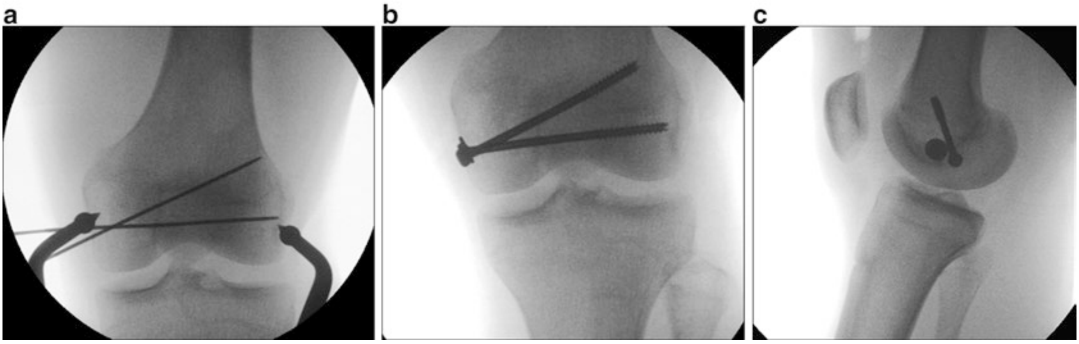

Fig. 12.5 (**a–c**) Fluoroscopic images from same patient in Figs. 12.1 and 12.3 demonstrating two-screw construct with one transphyseal screw to optimize stability

lateral to the central weight-bearing surface of the lateral femoral condyle, but may also extend to include it. While each fragment is different, with regard to its shape, its condition, and the amount of bone that it may contain, even those fragments with minimal subchondral bone or no bone, which is more common in younger patients, may heal with appropriate fixation, if pursued early enough after injury. The first 2 weeks is the optimal time for fixation, but fragments with substantial portions of bone can be successfully fixated up to 6 weeks or so, provided that there is not excessive cartilage degradation. Synovial fluid intravasation into the chondral tissue can cause swelling of the size of the fragment, so steps may need to be taken to trim down a fragment to fit into the native condylar bed off of which it sheared, with the understanding that future contraction of the fragment back toward its original, native size is likely to occur, and any final implant position should be decided with this possibility in mind.

Fixation can be performed through arthroscopic or open techniques. Implant options include k-wires, cannulated or solid metal screws, variable pitch headless screws, or bioabsorbable pins [27–29], tacks, or screws, which have the advantage of not requiring implant removal but the disadvantage of being radiolucent, which means that MRI may be necessary in certain cases to confirm implant position in the postoperative period [30]. For non-bioabsorbable implants, hardware removal is usually performed at some point after fracture healing, though headless compression screws may be buried beneath the superficial level of the cartilage and may be retained [31]. Whereas fixation of chondral-only fragments was not traditionally pursued due to concerns about getting cartilage to heal to bone, newer evidence supports the notion that chondral-only fragments may be able to heal in children or adolescents if early refixation is pursued [32, 33].

Complications

Complications associated with distal femoral fractures are not uncommon, with those related to premature physeal arrest being the most common. More physeal arrest cases are incomplete, or partial, than complete arrests across the entire physis, so angular deformity is more common than frank leg length discrepancies. A large study of over 550 fractures reported a 52 % chance of growth disturbance [4], with other studies quantifying the rates based on Salter-Harris types I (36 %), II (58 %), III (49 %), and IV (64 %). While non-displaced fractures also have surprisingly high rates of growth disturbance, it is around 1/4th as likely as displaced fractures. While infants under 2 years old are an at-risk group, due to the flat shape of the physis at this age, the highest risk group are preadolescents with more than 2 years of growth remaining, in whom even minor growth disturbances can manifest themselves clinically through the peak period of pubertal growth. Older adolescents may have similar degrees of arrest that do not progress due to the limited continued growth.

Close follow-up through skeletal maturity is the best way to ensure early diagnosis and timely management of physeal disturbances. Hips-to-ankles alignment radiographs or assessments with modern, low-radiation, EOS CT imaging may be helpful to detect abnormalities, sometimes before clinically apparent on physical exam. When physeal bridging or "bony bars" are suspected and confirmed with CT or MRI, management depends on the size and the amount of growth remaining. Those that are less than 50 % of the physeal surface area in a child with more than 2 years of growth remaining should likely undergo excision and fat- or soft-tissue interposition to attempt to restore physeal function on that side of the distal femur. Restoration of growth is achievable, sometimes with spontaneous correction following bar excision to an acceptable degree of improvement of angular deformities and leg length discrepancies. Interestingly, there is a significant range of reported success rates with such techniques, with the literature suggesting that anywhere from 25 to 80 % will regain physeal function following bar excision [34–36]. However, staged or concurrent hemi-epiphysiodesis may need to be performed to optimize angular alignment, as may contralateral epiphysiodesis at a later juncture to restore equal leg lengths. More severe physeal arrests that are more than 50 % of the surface area may require contralateral epiphysiodesis or, in a younger child, consideration of leg-lengthening techniques to address more severe projected discrepancies. Older adolescents who present in delayed fashion with closing or closed growth plates may also require lengthening to address clinically significant leg length discrepancies (usually over 2–3 cm) or distal femoral osteotomies to address clinically significant angular deformity (usually 10–15°). However, the exact amount of angulation and/or discrepancy that may be "clinically significant" may be different for different children, and care should be individualized to the patient and family. The topic of treatment of growth arrests and deformity represents a huge area of study unto itself, and is not done justice with the above oversimplification of some basic principles. Awareness of the high potential for such clinical sequelae is the key takeaway, with a number of treatment options available to optimize long-term lower extremity function in the young patient.

Another common complication of Salter-Harris fractures of the distal femur is knee stiffness, which is best prevented with early range-of-motion exercise, usually best pursued through physical therapy within 4 weeks of the injury or fixation surgery. If detected later as a complication, it can often be overcome with an aggressive therapy regimen and dynamic splinting during the first 3–4 months after injury. Beyond this time frame, consideration should be made toward arthroscopic lysis of adhesions and manipulation under anesthesia, particularly in the older adolescent. Increasing flexion can sometimes be achieved over the course of up to 6 months in younger children, such as those under 12 years old or so. Should arthroscopy, lysis, and manipulation need to be pursued in this age group, care must be taken to avoid distal femoral physeal injury through excessive manipulation in skeletally immature patients [20, 37].

Other, less common complications include infection, which is best avoided by burying k-wires for later removal or removing them within 4 weeks, as well as loss of reduction, which is rare with the use of adequate pin sizes and achieving anatomic reduction. Vascular injuries are uncommon, but can occur in association with severely displaced fractures, particularly in the anterior direction, in which the metaphyseal fragment can kink or tear the popliteal artery which is stretched anteriorly or draped over a bony spike. Early detection, appropriate workup, expeditious involvement of vascular surgery consultation services, and careful monitoring for compartment syndrome of the leg, if not prophylactic fasciotomies (indicated in the setting of more than 4–6 h of ischemia time), are all essential to avoiding catastrophic sequelae. Nerve injuries are also rare, with the peroneal nerve being the most commonly affected, also with anterior epiphyseal displacement, specifically anteromedial. Direct trauma to the peroneal nerve may occur as well, in the typical valgus knee direct blow phenomenon. Either mechanism tends to warrant the use of an ankle foot orthosis and/or multi-podus boot (if the motor branches are affected) and observation, with spontaneous resolution in most cases within 3 months. If no recovery is seen within this time, an electromyogram and potentially further treatment is warranted, depending on the findings.

Complications following osteochondral fracture fixation include stiffness, implant-related complications, such as migration or prominence, and local degenerative joint disease at the site of chondral fissures or on the margin of chondral defects in cases of removed fragments. Of course, if the fracture occurred in association with a dislocation event, recurrent patellar instability may be the most common complication, with the possibility of further osteochondral injury. Some studies have shown that concomitant medial patellofemoral ligament repair decreases the risk of recurrent instability [38, 39]. However, other studies have disputed this notion, which remains controversial [40–44].

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Evaluation and Management of Pathologic Femur Fractures in Children

13

Bryan Snyder and Megan Anderson

Introduction

While the vast majority of femur fractures in children occur from moderate to high-energy accidental trauma, pathologic fractures are not uncommon and tend to occur in two settings: (1) fracture through a localized area of compromised bone integrity, usually secondary to a benign bone cyst or non-malignant tumor in the femur; or (2) fracture in the setting of globally or systemically compromised bone integrity, usually secondary to underlying neuromuscular disease, disuse osteoporosis, or a specific named metabolic bone disease.

This chapter will explore both of these scenarios, providing some brief background into principles specific to orthopedic oncology, as well as pearls in the management of fractures occurring in the pediatric neuromuscular disease population, which can create unique challenges for orthopedic caregivers.

Etiology of Pathologic Fractures

Pathologic fracture risk is dependent on both the strength of the bone and on the loads applied to the bone. A fracture may occur when the load applied to the bone during a specific activity exceeds the load capacity of the bone. The load-bearing requirement of the bone depends on patient size, patient weight, and patient activity level. The ability of the bone to resist axial loads, as well as bending and twisting movements, is determined by the quantity and spatial distribution of mineralized bone tissue. Rigidity is the quantitative structural parameter that incorporates both the material and geometric properties of the bone; it is calculated as the integrated product of the bone tissue modulus of elasticity (stiffness) and bone cross-sectional geometry [1]. The stiffness and strength of bone tissue depend on the mineral density of the bone tissue [2, 3]. The bone geometry is represented by the cross-sectional area and moment of inertia [4]. The moment of inertia quantifies how the bone tissue is distributed in space; it varies as the fourth power of the distance of the bone tissue relative to a specific bending axis. Therefore, the resistance of the bone to bending and torsion dramatically increases as bone tissue is distributed away from that bending axis (e.g. cortical expansion induced by a bone cyst or periosteal expansion of fracture callus), and conversely is severely

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diminished for narrow, gracile bones (e.g. osteogensis imperfecta). The loading mode also influences the risk for bone fracture. Mineralized bone tissue is stiffest and strongest in compression, weaker in tension, and weakest in shear [5]. Torsional moments that induce tensile and shear stresses within the bone tissue will cause the bone to fracture more easily than axially applied loads that induce compressive stresses within the bone tissue. It is the *least rigid* segment through the bone that dictates the load capacity of the entire bone, i.e. fracture occurs at the segment through the bone with the lowest combined bone mineral tissue density and cross-sectional geometry. The metaphysis comprised of low-density, porous trabecular bone that is intrinsically weaker and metabolically more active than the dense cortical bone comprising the diaphysis and thus is frequently the site of pathologic fractures.

Pathologic fracture implies that the affected bone failed prematurely, unable to resist loads it typically would support. Therefore, the occurrence of a pathologic fracture implies that there have been changes to the bone tissue material *and/or* bone geometry that significantly decreased the structural rigidity of the bone in the region where the fracture occurred, and should prompt an intensive investigation as to the etiology of the underlying bone pathology. Any condition that alters the material properties of the bone (e.g. medications, osteogenesis imperfecta, osteoporosis, fibrous dysplasia) and/or the geometry of the bone (e.g. tumors, infection, skeletal dysplasia) can result in a pathologic fracture.

Pathologic fractures in children are often a consequence of benign bone neoplasms, simple bone cysts, infection, or disuse osteoporosis. Malignant neoplasms are less common, but often present with a pathologic fracture [6]. Metastatic cancers are relatively rare in children, and are associated with neuroendocrine cancers, leukemia, and lymphoma. The diagnosis of a pathologic fracture in children can be challenging, due to difficulties in soliciting a history of prodromal symptoms or predisposing factors. It has been estimated that 30–75 % of the bone matrix must be destroyed before an osteolytic lesion can be seen on plain radiographs. Since trabecular bone strength varies approximately as the square of bone apparent density, strength reductions of 50–90 % occur by the time an osteolytic lesion is evident radiographically [7]. Therefore, a high level of suspicion and a thorough history is essential to diagnose the underlying cause of a pathologic fracture.

Patient Evaluation

Important issues related to evaluating a patient who may have sustained a pathologic fracture are considered. The listed elements are not comprehensive or necessary for all patients, but rather instructive of the issues to be evaluated when conducting the work-up of a suspected pathologic fracture with regard to history, physical examination, radiolographic, and laboratory findings.

1. *History*
    (a) *Age*
    (b) *Fracture history*: number of fractures; age of fractures; circumstances (trauma vs. pathologic)
    (c) *Chronic disease*: seizures, diabetes, renal failure, liver disease, malabsorption
    (d) *Medications*: type and duration of use (especially anti-seizure drugs); vitamins, calcium supplementation, aluminum containing antacids (bind phosphate)
    (e) *History of blue sclerae*: osteogenesis imperfecta
    (f) *Dietary history*: especially intolerance to milk and dairy products, feeding difficulty, caloric intake, calcium, vitamins C and D content of prepared formulas, supplements, and tube feeds
    (g) *Activity level*: load bearing status - independent ambulation, assisted ambulation, nonambulatory; sports activities, high vs. low energy injury
    (h) *Family History*: family member with frequent fractures, short stature or skeletal deformities; family members with premenopausal osteoporosis and/or male osteoporosis; known familial genetic/heritable traits affecting connective tissues,

mineral metabolism, endocrine function; osteogenesis imperfecta or skeletal dysplasia
   (i) *Pubertal status*: signs of puberty—pre- vs. post menarche, secondary sexual characteristics
   (j) *Review of Systems*: screen for undetected chronic disease
2. *Physical Examination*
   (a) Height, weight
   (b) Sclera (blue/gray) and dentition
   (c) Tanner staging (pubic hair, breast development)
   (d) Extremities: bowing/deformity, widened peri-articular bone segments, joint stability, ROM range of motion/contractures
   (e) Neurologic: level of functionality, motor examination, gait and station
3. *Laboratory Data*
   (a) Complete blood count (CBC), differential, erythrocyte sedimentation rate (ESR), C-reactive protein (CRP)
   (b) Electrolytes, bicarbonate, glucose, blood urea nitrogen (BUN), creatinine, aspartate aminotransferase (AST), alanine aminotransferase (ALT)
   (c) Thyroid stimulating hormone (TSH), thyroxin (T4), thyroxine-binding globuline (TBGI), gonadotropins (luteinizing hormone, follicle-stimulating hormone), testosterone (boys >9), estradiol (girls >8)
   (d) Calcium (Ca), phosphorous (Phos), magnesium, alkaline phosphate, albumin
   (e) Parathyroid hormone (PTH), 25-hydroxy vitamin D, 1,25-hydroxy vitamin D
   (f) Urine: Ca, Phos, Creatinine (calculate urine Ca/creatinine ratio)
4. *Imaging Studies*
   (a) *AP and lateral radiographs of affected regions of axial and appendicular skeleton*: document fracture status, bone deformities (bowing, rugger jersey spine), widened growth plates, physeal cupping, Looser's zones (pseudofracture of compression side of bone), periosteal elevation, and corner sign
   (b) *Quantitative computed tomography* (*QCT*): CT scan obtained in conjunction with calcium hydroxyapatite calibration phantom in order to convert X-ray attenuation to equivalent bone density. Allows calculation of true bone density (g/cc) and assessment of trabecular and cortical bone windows separately. The cross-sectional structural rigidity of the bone can be calculated to predict fracture risk and load carrying capacity of the bone [8]. Protocols have been developed to decrease radiation dose.
   (c) *Dual-Energy X-ray Absorptiometry* (*DXA*): The interpretation of DXA in children is more complicated than in adults since bone mass is a moving target that varies with the child's age, sex, and pubertal status. There are few normative BMD data sets that take into account patient weight and/or pubertal status in addition to chronological age [9]. It is well known that bone age is not equivalent to chronological age in many growing children. In particular, choosing appropriate reference values is challenging in cerebral palsy children whose growth and puberty are delayed. Most DXA software programs calculate a BMD T-score, or standard deviations from the healthy adult mean. Use of a *T*-score in a child is as inappropriate as comparing a child's height to that of an adult [10]. BMD from pediatric subjects should be assessed in terms of *z*-scores, the standard deviation from age-matched controls [10]. Unfortunately, most DXA software programs include little or no pediatric reference data from which z-scores can be calculated. Calculated *z*-scores in children vary depending on the software, DXA equipment, and normative data set used. Laura Bachrach's group at Stanford has gathered normative data for 423 healthy adolescents and young adults (age 9–25 years) at the lumbar spine, hip, and whole body [11].

Henderson et al. found that hip and knee flexion contractures, previous hip surgery with metallic hardware, and/or excessive motion prevented reliable assessment of proximal femur BMD in >80 % of patients with severe cerebral palsy (CP) [12]. In a different heterogeneous series of over 300 children with assorted medical and physical conditions, Henderson et al. also noted that BMD of the lumbar spine was an unreliable predictor of bone status at the proximal femur [13]. To address this problem, the authors developed a technique to measure distal femur bone density in the lateral projection [14]. Three separate regions within the distal femur are examined independently: Region 1 (predominantly trabecular bone) is located within the metaphysis just proximal to the growth plate; Region 2 is the region of transition between the broad metaphysis and narrow femoral shaft; Region 3 (predominantly cortical bone) is the distal portion of the femoral diaphysis [14]. Normative data from 256 children and adolescents have been collected at the distal femur site [15]. The distal femur lateral BMD provided more predictive information regarding femoral osteopenia and fracture risk than lumbar BMD, however measurement of distal femur BMD in children with severe CP was complicated by motion artifact secondary to limited cooperation and/or involuntary muscle spasm [16].

(d) *MRI*: Radiofrequency pulse sequence in presence of a strong magnetic field can be used to generate three-dimensional images, which is the basis of the MR imaging. Bone structures as well as soft tissue can be visualized by MRI, but one needs to be aware that only the trabecular network can be seen and not the mineralized bone tissue [17], which appears as a signal void in midst of the high signal intensity of the bone marrow. Since higher water content increases MR signal intensity, MR imaging is widely used to determine the extent of soft tissue involvement or the inflammatory response within the bone marrow [18].

(d) *Nuclear Medicine Studies*: Positron emission tomography (PET) detects the metabolic activity of the cells by visualizing the metabolism of fluorodeoxy glucose (FDG) [19]. The cells with high turnover and metabolic activity can be detected using this modality. Cancerous cells have abnormal metabolism that can be detected by PET. This technique is more useful for the follow-up and detecting remission or reactivation of the pathology. It has very limited role in the initial diagnosis of pathologic fracture.

The orthopedic surgeon should pay special attention to the following key points [20] when considering the etiology of a pathologic fracture:

1. Age of patient, in years:
    - Generalized Causes:
        - Neuromuscular diseases (disuse osteopenia) **0–20 yrs. of age**
        - Osteogenesis imperfecta **0–20 yrs. of age**
        - Medications (steroids, diuretics, anti-seizure drugs) **0–20 yrs. of age**
        - Nutritional issues (milk intolerance, vitamin D deficiency), short gut **0–5 yrs. of age**
        - Rickets **5–20 yrs. of age**
        - Dietary deficiencies **5–20 yrs. of age**
        - Osteopetrosis **5–20 yrs. of age**
        - Bone marrow diseases **5–20 yrs. of age**
    - Benign Lesions:
        - Osteomyelitis **0–5 yrs. of age**
        - Eosinophilic granuloma **0–5 yrs. of age**
        - Unicameral bone cyst **5–20 yrs. of age**
        - Aneurysmal bone cyst **5–20 yrs. of age**
        - Non-ossifying fibroma **5–20 yrs. of age**
        - Osteochondroma **5–20 yrs. of age**
        - Fibrous dysplasia **5–20 yrs. of age**
        - Enchondromatosis **5–20 yrs. of age**
        - Chondroblastoma **5–20 yrs. of age**
        - Giant cell tumor **5–20 yrs. of age**
    - Malignant tumors
        - Metastatic tumors (neuroblastoma, Wilms) **0–5 yrs. of age**
        - Leukemia **0–20 yrs. of age**
        - Ewing Sarcoma **0–20 yrs. of age**

  - Lymphoma **5–20 yrs. of age**
  - Osteosarcoma **5–20 yrs. of age**

2. Pain characteristics:
   - Duration
     - Increasing pain for days or weeks
     - Intermittent or chronic pain
   - Exacerbating or alleviating factors
     - Osteoid osteoma: rapid improvement of pain with NSAIDs or aspirin
     - Stress fracture/benign lesions: improve with decreased weight-bearing/activity
     - Night pain—infection, neoplasm
   - Inflammatory signs
     - Infection: redness, increased temperature and swelling in the presence of a bony lesion
   - Neurogenic/neuropathic
     - Neurologic signs (dysesthetic, focal numbness, weakness if the lesion is large and compressing on peripheral nerve)
3. Imaging studies:
   - Location in long bones
     - Epiphysis:
       Infection
       Chondroblastoma (physis open)
       Giant cell tumor (physis closed)
     - Metaphysis:
       Most tumors
     - Diaphysis:
       Fibrous dysplasia
       Adamantinoma/Osteofibrous dysplasia (tibial diaphysis)
       Histocytosis/eosinophilic granuloma
       Ewing sarcoma
       Lymphoma/leukemia
   - Location in Spine
     - Anterior (Body)
       Eosinophilic granuloma/Langerhans cell histiocytosis
       Infection
       Leukemia
       Hemangioma
       Giant cell tumor
       Chordoma
     - Posterior elements
       Aneurysmal bone cyst
       Osteoid osteoma/osteoblastoma
       Osteochondroma
   - Size and extent
     - Aggressive lesions grow faster and tend to be larger. Fibrous dysplasia is an exception in that it is typically not aggressive but can involve a large extent of the bone and/or several bones.
   - Pattern of bone involvement
     - Lytic lesions (unicameral bone cyst, etc.) make the bone more prone to fractures than blastic lesions (osteoblastoma, etc.).
   - Bone response
     - Cortical thickening and new bone formation to compensate the biomechanical force changes, can delay or perhaps prevent the pathologic fracture if bone is affected for long enough period of time without excessive forces.
   - Soft tissue response:
     - Presence of a soft tissue mass may be ominous due to the increased chance of malignancy and also increased fracture risk since the cortical bone next to the mass is usually weakened or destroyed.

Generalized Causes

Immobilization and Disuse Osteopenia

Bone that is “unloaded” by virtue of cast immobilization or non-weight bearing will resorb as much as 44 % of the mineralized trabecular bone fraction, especially at the metaphysis [21, 22]. This significantly reduces the load capacity of the bone. Refracture due to this phenomenon can persist for 6 months after the injury [22].

Bone density is lower in non-ambulatory children with cerebral palsy and other neuromuscular conditions such as spinal bifida, muscle dystrophies, and hereditary motor neuropathies than in non-disabled children [12, 15, 16, 23, 24]. Multiple factors contribute to the problem, including prolonged periods of immobilization, non-ambulatory status, poor nutrition affecting intake of calcium and vitamin D, pervasive neurologic injury, and extent of physical disability [12, 13, 15, 16, 25–32]. The finding that children with cerebral palsy who ambulate independently have a higher bone density than children who are non-ambulatory suggests that lack of ambulation may be the single most important factor contributing to low bone density in children with cerebral palsy [16, 26]. Aside from limited weight-bearing ambulation during skeletal growth, oral motor dysfunction increases feeding difficulty for many individuals with neuromuscular conditions [33–35]. Poor nutrition and low calcium intake are common and may contribute to poor mineralization of bone tissue [12, 36]. Use of anticonvulsant medications such as Dilantin and Carbamazepine adversely affect bone mineralization by reducing the production of 25-hydroxyvitamin D [37–39]. Premature birth, an important risk factor for cerebral palsy, has been independently associated with the metabolic bone disease (the “rickets of prematurity”) [40]. Even when evaluated as older children, these formerly low birth weight, premature infants continue to have lower than normal bone mineral content [41]. Physically impaired individuals also participate in fewer outdoor activities and have less exposure to direct sunlight, which is critical for the endogenous formation of cholecalciferol (vitamin D_3) from 7-dehydrocholesterol [42]. Using stepwise regression analysis, Henderson et al. found (in decreasing order of importance) that severity of neurologic impairment (graded by the Gross Motor Functional Classification level), increased feeding difficulty, use of anticonvulsants, and lower triceps skinfold measurement all independently contributed to lower bone density in the distal femur [16]. Routine hospital laboratory tests did not identify children with low bone density, and serum 25-hydroxyvitamin D levels did not correlate with bone density as measured by dual-energy X-ray absorptiometry (DXA) at the femur or lumbar spine.

Although some studies find that the actual fracture rate in children with spastic quadriplegia is similar to that of normal children [43], the fracture incidence is highest in the most severely handicapped individuals [16, 44]. The occurrence of a fracture is often the result of low bone density, stiff joints, and poor balance, leading to falls and violent seizures [45]. The long bones of the appendicular skeleton in these children are smaller, the cross-sectional diameter narrowed, and the cortices thinned. Therefore, both the bone tissue material properties and geometric structural properties of the skeleton are compromised. The vast majority of fractures in these children is therefore pathologic and occurs with minimal trauma. Fractures usually occur during daily management of these children while merely being turned in bed, dressing, or being transferred [24, 44, 46]. “Spontaneous fractures” of the long bones have been reported [12, 24, 36] and in one study of institutionalized children with cerebral palsy, the cause was not known for over 50 % of the fractures [44]. The majority of fractures are in the lower extremities, most commonly in the femoral shaft, which is a relatively uncommon fracture site in children without disabilities (less than 2 % of fractures) [44, 47]. In various reported series of non-ambulatory children and young adults, approximately 25 % had sustained a femur fracture at some time in their life [16, 31, 43, 48]. Usually these fractures are treated non-operatively, but hospitalization may be required as these are more frequently complicated by malunion and/or refracture than the general pediatric population, as well as decubitus ulcers of the sacrum, heel, and thigh [44, 48].

Treatment for Disuse Osteopenia

Physical activity increases bone density in growing children [47, 49]. A logical intervention for children with cerebral palsy is weight bearing to counteract the ill effects of immobilization. Standing equipment, specifically standers, are recommended by physical therapists for children who are not able to walk or stand independently. Although standers are assumed to help prevent fractures and increase bone density, few studies have been performed to support these assumptions. Furthermore, the results of these few studies examining the effect of standing programs on bone density in individuals with quadriplegia are conflicting. Some studies have shown an increase in bone density with physical activity in children with cerebral palsy [26, 50]. However, standing programs for patients with spinal cord injury did not show an increase in bone density [51, 52]. The correct dose of weight bearing or exercise remains unknown.

Pharmacologic Treatment

1. Optimal Calcium Requirements [53]

Age group	Optimal daily intake Ca (mg/day)
(a) Birth to 6 months	210
(b) 6–12 months	270
(c) 1–3 years	500
(d) 4–8 years	800
(e) 9–18 years	1300

N.B. 1 cup milk (240 cc) = 300 mg Ca

2. Vitamin D_2 supplement 400 IU of ergocalciferol (vit D_2) if NO evidence for rickets
    (a) 1000–2000 U/day ergocalciferol if nutritional vit D deficiency
3. Pamidronate (3-amino-1-hydroxypropylidene bisphosphonate)
    (a) Acts to inhibit bone resorption by inactivating osteoclasts
        - Binds to bone mineral directly—inhibits both formation and dissolution of calcium phosphate crystals
    (b) Has been used with success in osteogenesis imperfecta, steroid-induced osteoporosis and JRA [54–56]
    (c) Double-blinded, placebo-controlled, clinical trial in six age-matched (6–16 years) pairs non-ambulatory children with severe CP [57]
        - Drug/placebo IV daily for 3 consecutive days, repeated at 3-month intervals for 1 year
            - Pamidronate 1 mg/kg body wt (but not less than 15 mg or more than 30 mg) administered over 3–4 h in volume of 400 cc
            - All patients received 1000 mg Ca, 400 IU of calciferol, 1 cc Poly-Vi-Sol
        - Evaluation by BMD at distal femur and lumbar spine over 18 months
        - Differential response in spine vs femur, trabecular bone vs cortical bone (Function of bone remodeling activity)
            - Greatest increase in distal femoral metaphysis: 89 ± 21 % pamidronate vs. 9 ± 6 % in saline control group; lumbar spine: 33 ± 3 % pamidronate vs. 15 ± 5 % saline. No statistically significant change at distal femur diaphysis.
        - No evidence of impaired mineralization (widened growth plates) or impaired remodeling (funnelization metaphyseal–diaphyseal junction).

Medication-Related Osteoporosis

Medical treatments for cancers, including chemotherapy (ifosfomide, methotrexate, etc.), corticosteroids, and radiation (which can cause radiation-induced hypogonadotropic hypogonadism, for example) can lead to iatrogenic osteoporosis. Osteopenia is initially observed in the trabecular bone comprising the metaphyses of long bones [58–60], but can occur later in the cortical bone comprising the diaphysis. Pathologic fatigue fractures occurring in the long bones, induced by chemotherapy, have been misdiagnosed as relapsing leukemia [61]. Preventive measures, such as supplemental vitamin D, increased physical activity, and the judicious use of bisphosphonates are indicated [59, 60]. If a fracture occurs or if a patient has focal bone pain without fracture, discontinuing methotrexate is advisable, if possible [58].

Rickets

Vitamin D has a pivotal role in bone metabolism, and any abnormality in its metabolic cascade or deficiency can result in rickets. It can cause secondary hyperparathyroidism which manifests with cyst formation and bone erosion. The provisional calcification zone in the physis widens due to mineralization failure. There are many types of rickets including: vitamin D-dependent, vitamin D-resistant, vitamin D deficiency, renal osteodystrophy, and gastrointestinal. They share common features such as epiphyseal displacement and pathologic fractures, but identification of the specific cause is necessary for proper treatment [62, 63].

Nutritional rickets is caused by inadequate vitamin D intake and not receiving adequate exposure to sunlight. Treatment of fractures in this patient population should include oral vitamin D and calcium supplements. Rickets due to malabsorption is commonly seen in celiac disease, in which the absorption of fat-soluble vitamins, including vitamin D, is affected. Administration of calcium gluconate and vitamin D_2 is necessary to facilitate fracture healing and to ameliorate fracture risk in these patients.

End-stage renal disease is commonly associated with renal osteodystrophy and can manifest as rickets and secondary hyperparathyroidism. Young children often present with genu varum or valgum. In addition to widened physes, and generalized osteopenia, osteoclastic cysts, or brown tumors, can be seen in the metaphysis. This osteitis fibrosa cystica predisposes patients with end-stage renal disease to pathologic fractures. In treating these fractures, internal fixation with plates or IM devices is better than external means such as casting [64]. However, optimizing medical management of the end-stage renal disease is required to facilitate fracture healing, including adjusting phosphate, ruling out aluminum toxicity due to administration of aluminum-based phosphorous chelating agents, and optimizing vitamin D levels. Aluminum toxicity results in abnormal and defective mineralization of bones and increases the risk of fracture [65]. Infection risk is increased in these patients, so prophylactic administration of hepatically metabolized antibiotics should be administered perioperatively [66].

Osteogenesis Imperfecta

Changes in the formation of Type 1 collagen cause osteogenesis imperfecta (OI). Alterations in various genes have been described including COL1A1, COL1A2, and IFITM5. Patients with OI demonstrate a wide spectrum of clinical manifestations, including fragile bones, skeletal deformities of the axial and appendicular skeleton, hearing defects, muscle atrophy, ligamentous laxity, prominent sternum, triangular facies, and basilar invagination. Blue sclera has been described as a classic finding in OI (in types IA, IB, and 2), but it is important to remember that it can be seen in normal infants, and other diseases such as osteopetrosis, Ehlers-Danlos, Marfan, and hypophosphatasia [67]. While Silence and others have classified types of OI based on modes of inheritance, and clinical manifestations [68–71], for practical purposes the types can be divided into severe and mild forms. The most severe forms are autosomal recessive. These patients present with multiple perinatal fractures of the axial and appendicular skeleton, and affected patients rarely go on to walk. The autosomal dominant forms of the disease are more common and less severe. These patients ambulate but sustain multiple long bone fractures, often throughout childhood, that often result in deformity. Radiographic evaluation demonstrates marked osteopenia, narrow bones with thinned cortices in the more severe forms of OI. Angular deformity of the long bones, with cystic areas, are evidence of multiple previous fractures. A fairly specific radiologic finding is the existence of wormian bone in the skull (abnormal intrasutural bone, which is usually found around the lambdoid suture) and avulsion fractures at tension apophyses such as the olecranon, greater trochanter, and tibial tubercle. Bones in various stages of healing after clinically occult fractures and fracture callus formation without the presence of fracture have also been reported [67]. These findings may also present in child abuse, which remains an important differential diagnosis in neonatal fractures.

OI has a higher association with osteosarcoma; therefore, biopsy is indicated for any aggressive-appearing lesion that involves a soft tissue component. Surgical treatment is frequently indicated to treat pathologic fractures and associated skeletal deformities in patients with OI. Treatment involves prophylactic splinting of the bone to correct or prevent deformity, decrease fracture risk and lessen pain. Elongating intramedullary rods, often inserted concurrently with corrective osteotomies , are used to achieve this goal. Telescoping devices with different mechanisms of action are available [72, 73]. The advantage of self-elongating systems is that they can accommodate growth of the patient. However the telescoping mechanism has been associated with increased rates of device failure compared to standard intramedullary rods. Nonetheless these systems have reduced the number of fractures following instrumentation [73].

Scurvy

Depletion in vitamin C from lack of dietary intake for 6–12 months will result in scurvy. The musculoskeletal system is affected in 80 % of patients who can present with hemarthrosis, arthralgia, myalgia, and hematomas in muscles. Significant demineralization with radiographic evidence of osteonecrosis, osteolysis, and osteopenia is present [74]. A Frankle line, which is a dense white line near the physis, may be seen on plain radiographs. Fractures are commonly juxtaepiphyseal, near a Frankle line [75].

Osteopetrosis

Reduced osteoclastic activity combined with normal osteoblastic function can result in increased bone density. In osteopetrosis, the bones are brittle and prone to pathologic fractures [76]. Imaging studies show chalk-like, dense bones. Long bones are marble-like and, due to the lack of remodeling, the ends of the bones have an Erlenmeyer flask shape. Dense bone at the endplates of vertebral bodies with relatively radiolucent regions in the middle gives the spine a “rugger jersey” appearance. To address fractures in this group of patients, standard principles should be followed, but there is a higher likelihood of delayed union.

Benign Bone Tumors

Benign skeletal neoplasms represent a diverse group of pathologic and clinical entities that vary greatly in aggressiveness and clinical behavior (Table 13.1) [6, 77]. The true incidence is unknown, but benign fibrous lesions such as nonossifying fibromas or fibrous cortical defects occur in up to 33 % of asymptomatic children evaluated by radiographs of long bones obtained for reasons other than surveillance of a lesion [78, 79]. After confirming that the lesion is benign, the orthopedist must decide whether the defect has weakened the bone sufficiently to cause undue risk of a pathologic fracture, and therefore whether prophylactic treatment is indicated [80]. There are no proven clinical or radiographic guidelines for predicting which children are at risk for pathologic fracture. The load capacity of the bone depends on its structural properties, which is determined by the material properties of the host bone tissue, the anatomic site, the geometry of the lesion relative to that of the host bone, and the aggressiveness of the neoplasm. The increased fragility associated with these lesions suggests either that the strength of the bone tissue surrounding the lesion is degraded and/or the stresses generated within the bone during loading are increased because of changes in bone geometry. No single radiographic parameter has been shown to accurately predict pathologic fracture through a benign bone lesion based on the patient’s age, the stage and activity of the lesion, the site of the lesion, the size of the lesion, and/or the percentage of cortical destruction [4, 8, 20, 63, 81, 82]. In a prospective study of 36 children with benign osteolytic lesions affecting the appendicular skeleton, there were no significant differences between fracture and nonfracture groups for any of the radiographic fracture risk parameters predicated on lesion size [1]. Radiographic criteria that account only for defect size were neither sensitive nor specific for predicting fracture risk. The accuracy of defect length ≥3.3 cm, defect width ≥2.5 cm, or more than 50 % cortical destruction measured on AP and lateral radiographs was at best a fair predictor, ranging from 42 to 61 %. This reflects the shortcomings of fracture risk indices based on lesion size alone, in that they fail to account for the compensatory remodeling of the host bone that occurs in response to the presence of the lesion. Fibrous lesions tend to induce cortical thickening around the margins of the lesion and septae form within the lesion that serve to buttress it against collapse. Cystic lesions induce periosteal expansion of the host bone that serve to increase the bone’s moment of inertia. These remodeling strategies partially compensate for the structural consequences of the lesion itself. Only by taking into account the structural properties of the entire bone containing the lesion can accurate fracture risk predictions be made. In contrast, biomechanical parameters derived from quantitative computed tomography (QCT) were 100 % sensitive for predicting fracture occurrence

Table 13.1 Benign bone conditions that can be associated with pathologic femur fracture in the pediatric population

Tumor	Radiographic features	Clinical features	Healing/treatment
Unicameral bone cyst	Purely radiolucent	Usually no symptoms until fracture	10 % heal with fracture healing
	Central metaphyseal		May require surgical treatment to heal
	"Fallen leaf" sign		Most heal with skeletal maturity
Aneurysmal bone cyst	Bubbly radiolucent lesion	Often painful prior to fracture	Require surgical treatment to heal
	Often eccentric		Option of sclerotherapy/embolization as well
	Most often metaphyseal		
	Thins and often expands cortex		
	Fluid-fluid levels on MRI		
Non-ossifying fibroma	Bubbly radiolucent lesion	Frequently an incidental finding	Healing adequate with fracture healing in about 10–20 %
	Sclerotic rim	Larger lesions may be painful due to fracture/stress change	May require surgical treatment to heal based on fracture risk
	Eccentric		Most heal with skeletal maturity
	Metaphyseal		
Langerhans cell histiocytosis	Radiolucent	Often painful prior to fracture	May heal with fracture or biopsy alone
	Central		Some treated with steroid injection
	Diaphyseal > metaphyseal		Skeletal survey and PET—eval for multiple bone lesions
			Oncology consult—eval for systemic involvement
Fibrous dysplasia	Ground glass	Mild achiness common	Will persist despite treatment
	Eccentric	May only have symptoms when stress fracture developing	Usually requires instrumented fixation, esp. in femoral neck
	Neck > diaphyseal		Can be polyostotic (bone scan)
Osteomyelitis	Radiolucent with variable reactive bone and periosteal change	Symptoms quite variable	Ensure not malignant tumor
	Metaphyseal > diaphyseal	May or may not have systemic symptoms, elevated WBC/inflammatory markers	Surgical debridement, antibiotics
Giant cell tumor	Eccentric	Rare in children	Definite diagnosis via biopsy before addressing the fracture
	Well-defined		
	Osteolytic		
	Little or no sclerosis		
	Epiphyseal > metaphyseal		

and QCT-derived biomechanical parameters were more specific than the radiographic criteria for predicting that a fracture would *not* occur through the lesion [1, 5]. When the ratio of minimum bending rigidity of the affected bone relative to the contralateral normal bone, EI_{lesion}/EI_{norm}, was less than 67 % (i.e. the lesion reduced the bending tolerance of the affected bone by more than 33 % compared to the contralateral bone at the homologous region), bending rigidity was the most accurate (94 %) single structural parameter for predicting fracture occurrence through the lesion. Logistic regression modeling revealed that the ratio of bending rigidities ($p < 0.0001$) and the ratio of torsional rigidities ($p < 0.0001$) were each highly informative QCT-derived biomechanical parameters for predicting fracture occurrence. This is consistent with clinically observed fracture patterns that implicate bending and/or torsion as common mechanisms of long bone failure.

Optimal treatment for benign bone lesions remains controversial. Depending on the lesion type, anatomic location, and suspected fracture risk, treatment may include: observation, restricted weight bearing or activity modification, bracing; intra-lesional injection of steroids or demineralized bone matrix with or without bone marrow aspirate; curettage and packing of the defect with bone graft with or without stabilization of the affected bone with hardware to prevent fracture [79, 82–97]. Two common lesions, the unicameral bone cyst and the non-ossifying fibroma, occasionally heal spontaneously after fracture (<10 %).

Unicameral Bone Cyst (UBC)

Metadiaphyses or metaphyses of long bones are the usual location for UBCs, also referred to as "simple bone cysts." The proximal femur and proximal humerus are the most commonly involved bones, and the lesion is generally central [98]. It has been suggested that obstruction of interstitial fluid drainage is the underlying cause for their formation [99]. Patients diagnosed with UBCs are most often in the first or second decade of life and are male, by a 2:1 ratio [98]. The most common presentation in more than half of patients is a fracture caused by a low-energy mechanism, or minimal trauma, without antecedent pain. The fracture pattern is often stable and incomplete. There may be a floating fragment of the fractured bone seen within the cyst cavity, which is commonly known as a "fallen leaf sign." While plain films are usually diagnostic, MRI can be used in atypical cases. Cysts will have intermediate to low signal on T1 and homogenously high signal on T2 sequences, with contrast enhancement only around the periphery [100].

Although UBCs are self-limiting and spontaneously resolve by skeletal maturity or soon thereafter, some require more proactive treatment due to persistent risk for fracture, especially those in the proximal femur, which frequently require open-plate fixation with bone grafting of the cyst. Alternatively, aspiration of the cyst material and serial injection of corticosteroid or single injection of injectable bone graft material, with or without aspirate material from the iliac crest, may be pursued, particularly for the non-weight-bearing lesions of the proximal humerus. Involvement of more than half of the diameter of the bone and cortical thinning have been suggested as indications for prophylactic treatment [101]. Depending on the location of the cyst and fracture, pathologic fractures due to UBCs can become complicated by growth arrest, malunion, and osteonecrosis of the humeral or femoral head [102].

Aneurysmal Bone Cyst (ABC)

ABCs are benign but locally aggressive lesions. They are rarely seen in patients older than 30 years, and three-quarters of cases are seen in those younger than 20 [103]. Males and females are affected equally. The femur is the most commonly involved bone, followed by the tibia, and the spine (predominantly lumbar vertebrae) [104]. Patients usually complain of pain and tenderness, and localized swelling may be present in the area of bony involvement. ABCs are not considered true cysts since they are blood-filled spaces with interwoven fibrous tissue. When localized adjacent to the physis, lesions may expand into the epiphysis. Imaging studies usually show a radiolucent, eccentric lesion in long bones with cortical erosion and neocorticalization.

This pattern results in a "honeycomb" or "soap bubble" appearance. Lesions in metatarsal and metacarpal bones are more central. In the spine, the posterior elements are more often involved than the vertebral body. MRI is helpful, but not pathognomonic. On T1 sequences, these cysts have low signal and multiple septations; on T2 sequences, high signal cystic area containing "fluid-fluid levels" are observed due to blood settling into its fluid and solid components within each cystic septation [105]. Recurrence rates are high after fixation of fractures, even with curettage and bone graft, especially in younger patients, so meticulous attention should be paid toward adequate curettage and/or high speed burring of the bony walls of the cyst, with or without introduction of an adjuvant sclerosing agent, such as phenol [106].

Non-ossifying Fibroma (NOF)

The most common benign bone tumor in children is a "fibrous cortical defect" or non-ossifying fibroma. NOFs are usually completely asymptomatic lesions seen incidentally on routine radiographs that are obtained for other reasons and have been estimated to be present in as many as 30–40 % of skeletally immature children. However, the prevalence in males is twice that of females, and pathologic fractures, when they occur, tend to do so in large lesions in boys between 6 and 14 years of age [107]. The metaphysis of the tibia and femur are the most common locations, and usually the lesion is parallel to the long axis of the bone. In radiographs, NOFs are eccentric, well-defined, radiolucent, metaphyseal lesions, often with a rim of reactive sclerotic bone around the intraosseous perimeter. These lesions become sclerotic and resolve with time with skeletal maturity [108]. However, for larger lesions that occupy more than 50 % of the bone's width, or those associated with stress fracture, curettage and bone grafting is advisable [93].

Langerhan's Cell Histiocytosis (LCH)

Histiocytosis is a disorder of the immune system with variable organ and skeletal involvement. The skeletal lesions associated with the condition were termed "eosinophilic granulomas," due to the prevalence of multiple eosinophils seen histologically. More recent understanding of this disorder has resulted in a revision of the nomenclature with LCH as the overarching term for the disease with specification of organ and/or skeletal involvement, solitary or multiple. In LCH with skeletal involvement, more than half of the cases are found in patients between ages of 1 and 15 years, with a peak in incidence between 1 and 4 years of age. It has slightly higher prevalence in males [109]. Pain is the most frequent presentation and LCH can affect either axial or long bones, most commonly humerus and femur. Tenderness at the site can be an examination finding, but there are rarely palpable masses. Radiologic findings are highly variable; hence the name "great imitator" has been given to these lesions. They are typically radiolucent with well-defined margins, with or without a sclerotic rim, and variable in size. The amount and type of periosteal reaction may raise concern for Ewing sarcoma, osteomyelitis, and hematologic malignancies. Involvement of the spine may result in "vertebra plana," in which there is complete collapse of the vertebral body. Being a great imitator, biopsy of these lesions is necessary for diagnosis. It is not uncommon to find multiple lesions in a patient. Patients with suspected or confirmed LCH should have a skeletal survey, PET scan, and full evaluation with a pediatric oncologist. Treatment of the skeletal lesions in LCH is often surprisingly simple: most lesions heal with biopsy alone or percutaneous steroid injection. Occasionally, larger lesions in weight-bearing bones may require curettage and bone grafting. Pathologic fractures are rarely seen in these patients, but when they occur, standard fracture care after definite diagnosis is advised. Spine lesions are variable in the need for treatment depending on the age of the patient and deformity: in young patients with one level involvement, a simple needle biopsy or steroid injection will often arrest the progression of the disease and allow enough residual apophyseal growth of the vertebral body to restore height; while in older patients with neighboring level collapse and/or deformity, stabilization and restoration of the anterior column may be required. LCH with organ involvement or multiple bone involvement is treated with chemotherapy [110].

Fibrous Dysplasia (FD)

Fibrous dysplasia is a non-neoplastic lesion characterized by replacement of normal bone with fibrous-osseous tissue. Although children may present with FD lesions at nearly any age, if it diagnosed in a younger age group there is a slightly higher likelihood of polyostotic involvement with a very young age of presentation, and accompanying endocrine problems can be seen. The triad of endocrine abnormalities, polyostotic FD, and café-au-lait skin lesions is termed McCune-Albright syndrome. In approximately 75 % of cases only one bone (monostotic) is involved, and patients present from late childhood to adulthood. FD is usually diagnosed in patients between the age of 5 and 15 years [111]. FD is very often asymptomatic, so lesions are identified incidentally; however, some can present with pain and/or deformity as a result of stress changes and pathologic fractures. Various bones can be affected by FD including the femur, tibia, radius, humerus, phalanges, ribs, facial bones, and pelvis. The spine is usually involved only in polyostotic FD. In radiographs, FD presents as usually centrally located, well-defined lesions in the diaphysis. "Shepherd's crook deformity," which is a varus deformity of proximal femur, is a well-known example of the radiologic findings of deformity associated with multiple stress fractures and stress changes over a long period of time. To distinguish between polyostotic and monostotic disease, bone scan is most helpful, since some lesions may not be seen in plain radiographs. Most of the fractures in monostotic FD will respond well to conservative treatment with immobilization, but the FD will persist and possibly lead to risk for repeated fractures. A surgical approach with curettage, grafting, and prophylactic hardware fixation is often indicated for polyostotic FD since the bone is usually significantly diseased with marked deformity or in areas at risk for repeated stress changes and fracture, such as the proximal femur [112]. FD can undergo malignant transformation to a sarcoma of bone in 0.5 % of patients within 15 years of diagnosis, according to one study [113]. Patients with symptomatic lesions thus may require monitoring and surveillance.

Giant Cell Tumor (GCT)

GCT is rare in the pediatric population. They are considered as benign-aggressive tumors, but can rarely metastasize to the lungs or present with multicentric involvement of several bones [114]. Females are affected more than males. Localized tenderness and pain can be found at the site. The lesions usually start in an eccentric location in the metaphysis and can extend into the epiphysis as they enlarge. The distal femur and proximal tibia are by far the most common location for this tumor. The other less common locations, in order of decreasing frequency, are proximal humerus and distal radius. They may also rarely be found in a central location in the bones of the hands, feet, ulna, or fibula. These tumors have 30 % incidence of pathologic fracture [115]. In radiographs, they appear as lucent, well-defined, metaphyseal lesions with extension to epiphysis. Even though they start as eccentric lesions, as they grow, they can occupy the whole width of the bone. Co-existence of a pathologic fracture at the site of these lesions increases the complexity of the treatment, but does not preclude treating the GCT similarly to non-fractured lesions with intralesional extended curettage, including the use of high-speed burring, and filling of the defect (with bone graft or cement). Recurrence rates are high in GCT and higher in cases of pathologic fracture. Multiple recurrences can lead to the need for bone resection and reconstruction, similar to malignant tumors.

Osteomyelitis

Osteomyelitis can mimic aggressive primary bone tumors. Hence, biopsy, gram stain, culture, and sensitivity are required for all aggressive osteolytic lesions to facilitate accurate diagnosis. Acute osteomyelitis can simulate conditions such as Ewing sarcoma and LCH. Chronic osteomyelitis (Brody's abscess) can simulate a nonossifying fibroma. Osteomyelitis has a bimodal age distribution: less than 2 years and between the ages of 8 and 10 years. Low oxygen tension and tortuous blood flow through the closed capillary loops at the junction of the physis and metaphysis provide an ideal platform for the hematogenous seeding of microorganisms at this location. It usually takes more than two weeks for osteoclastic bone resorption sufficient to be imaged on plain radiographs [116]. Bone scan has been used for early diagnosis with 63–90 % sensitivity [117]. MRI, with its ability to detect inflammation and fluid collections in the bone, has become the diagnostic method of choice with 98 % and 100 % sensitivity and specificity, respectively, in one study [118]. Fortunately, with early intervention and aggressive antibiotic administration, pathologic fractures due to osteomyelitis are rare. In North America, a pathologic fracture related to osteomyelitis in a child should raise the suspicion of chronic osteomyelitis, or neonatal osteomyelitis with congenital rubella or congenital cytomegalic inclusion disease [1, 119]. Pathologic fractures through infected bone can result in delayed union, malunion, and growth disturbance.

Malignant Bone Tumors

Pathologic fractures due to metastatic lesions to the bone are far more common than fractures caused by primary bone tumors in adults, but great care must be given to pathologic fractures in aggressive bone lesions in the pediatric population, as primary malignant bone tumors are more common in children than in adults (Table 13.2). Accurate diagnosis by biopsy and staging are critical for the treatment plan [120, 121]. Biopsy of the lesions can significantly increase the risk of fracture; hence, it should be done in an area of the least stress possible in weight-bearing bones, while still optimizing the diagnostic accuracy. Using a smooth-edged oval hole and sometimes filling the hole with cement may be advisable to reduce such risk [121].

Table 13.2 Radiographic features for benign versus malignant tumors associated with pediatric pathologic fracture

Benign	Malignant
Geographic	Permeative
No or simple periosteal reaction	Aggressive periosteal reaction—Codman's triangle, onion-skinning, sunburst, hair-on-end
No effect or mild cortical thinning on host bone	Host bone destruction
	Cortical thinning/erosion
No soft tissue mass	Soft tissue mass extending out of bone
Metaphyseal > diaphyseal	Metaphyseal > diaphyseal
Smaller	Larger

Osteosarcoma and *Ewing sarcoma* are the most common sarcomas of the long bones in the pediatric population. Advances in the imaging and chemotherapy treatment of sarcomas of bone in children have significantly improved making limb-salvage surgical techniques possible. There is debate whether pathologic fracture of these lesions should be a contraindication for limb-sparing surgery. The concern is that tumor cells would be disseminated by the hematoma at the site of the fracture, but some studies have shown that eventually these fractures heal with neoadjuvant chemotherapy, and the survival rate may not be affected by that. Chemotherapeutic response is probably a more important factor for survival and local control than the risks associated with pathologic fracture, though cases must be considered individually [122–124].

Leukemia is a common cancer in the pediatric population and accounts for more than one-third of all malignancies. The peak incidence age is 4 years. It commonly involves joints and bones, with 50–75 % of patients having radiographically evident involvement of the skeleton. Pathologic fractures are present in up to one-third of leukemia patients [125, 126]. The most frequent finding in radiographic imaging is diffuse osteopenia. Moth-eaten or confluent radiolucency can be seen due to osteolytic lesions. These lucent lesions are often associated with mildly aggressive periosteal reaction, and are most commonly seen in the metaphysis of the distal femur, medial neck of the femur, and diaphysis of the tibia and fibula [127]. The most common pathologic fracture in pediatric patients with leukemia is a compression fracture of the spine due to treatment-related osteoporosis (most common) or leukemic involvement (less common). The thoracic spine is most commonly affected.

In developing a treatment plan for pathologic fractures in leukemic patients, chemotherapy should be considered the first step, since most are stable microfractures which respond well with conservative supportive techniques as the leukemia itself is treated with the chemotherapy. Close observation and a non-surgical approach is advisable for most of the vertebral fractures as well [20].

Lymphoma (*Hodgkin* and *non-Hodgkin*) accounts for 10 % of malignant bone lesions in the general population, but is very rarely seen in individuals younger than 20 years of age. It affects males more than females. Pain is usually present before the lesion becomes detectable radiographically [20, 128].

Hodgkin Lymphoma (*HL*) affects the axial skeleton predominantly and more than half of the lesions are located in pelvis, thoracolumbar spine, ribs, and femur, where they present as lytic lesions. Langerhan's cell histiocytosis and Ewing sarcoma are within the differential diagnosis of HL in young patients. Bony sclerotic reaction may be evident and such a phenomenon in the spine can lead to an "ivory vertebra" appearance due to sclerosis of the whole vertebral body. MRI and CT scan are useful to evaluate the extent of tumor involvement and integrity of the cortex. Biopsy is essential for diagnosis, and treatment involves radiation and chemotherapy. Surgery is only advised for addressing pathologic fractures [128].

Non-Hodgkin lymphoma (*NHL*) can affect any bone. Lesions are lucent and usually coalesce with other lesions to form bigger lesions with a "moth-eaten" border. The differential diagnosis for NHL in a pediatric population includes Langerhan's cell histiocytosis, Ewing sarcoma, osteosarcoma, and osteomyelitis. Metastasis of neuroblastoma should be considered in patients younger than 10 years old. While the level of sclerotic bony response is less than HL, high-grade NHL can have this appearance and also present as an "ivory vertebra" [128]. It is important to distinguish primary NHL of bone from metastasized NHL, since primary NHL is potentially curable, whereas metastasized NHL has a high mortality rate. PET scan, MRI, and CT are valuable tools for diagnosis and staging. Biopsy is the cornerstone of the diagnosis. Treatment of NHL in children involves chemotherapy. Bone lesions are rarely radiated in children, unlike in adults. Surgery is reserved for pathologic fractures and rare cases of local recurrence [128].

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14

Evaluation and Management of Complications of Pediatric Femur Fractures

Marie-Lyne Nault and James R. Kasser

Complications of Proximal Femur Fractures

Proximal femoral fractures about the hip account for less than 1 % of all pediatric fractures [1], and are usually the result of high-energy mechanism. Because of the osseous and vascular hip anatomy unique to children, these fractures can result in various complications (Table 14.1).

Osteonecrosis

The most common complication after a hip fracture in children is osteonecrosis of the femoral head, or avascular necrosis (AVN). Table 14.1 shows the overall prevalence of osteonecrosis after hip fracture. A recent meta-analysis of 360 cases of pediatric hip fractures demonstrated that the two most significant risk factors for osteonecrosis are primary fracture type and age at the time of the injury [2]. A Delbet type 1 (transepiphyseal) fracture is at high risk of developing osteonecrosis, particularly if associated with displacement or dislocation. The prevalence of osteonecrosis varies between 38 and 100 % in type 1 hip fracture, depending on the reported series [3–7]. In a meta-analysis performed by Moon and Mehlman, the rate of osteonecrosis according to the Delbet classification was 38 % for type 1 (transepiphyseal), 28 % for type 2 (transcervical), 18 % for type 3 (cervicotrochanteric), and 5 % for type 4 (intertrochanteric), and an overall rate of 21 % [2]. The authors also reported that for each year of increasing age, older children were 1.14 time more likely to develop osteonecrosis [2]. Miller et al. reported from their series that children of 22 months and younger seem to have a better outcome of hip fractures in general [8]. Given these relatively high rates, however, any patient with a displaced femoral neck fracture should be followed closely, both clinically and radiographically, in the first 2 years after the injury to monitor for potential development of AVN, which may arise in a delayed fashion.

Many studies have shown that osteonecrosis, when it arises, is associated with a poor functional outcome [3, 9]. Once identified, there is no well-established approach to management of severe or debilitating cases. Treatment may range from core decompression, with or without vascularized bone grafting [1], multiplanar redirectional osteotomies [2], hip fusion, and hip

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Table 14.1 Complications of fractures of the proximal femur

Study	Mean FU	Mean age	AVN	Coxa vara	Coxa valga	Premature physeal closure	Greater troch	Nonunion	Infection
Kuo et al. [9]	4.9	11.1	48 % (11/23)	13 % (3/23)	9 % (2/23)	48 % (11/23)		0 % (0/23)	
Pape et al. [3]	11.1	11.8	7.1 % (2/28)	3.6 % (1/28)	7.1 % (2/28)			3.6 % (1/28)	3.6 % (1/28)
Moon et al. [2]			8 % (2/25)	4 % (1/25)	4 % (1/25)	16 % (4/25)	4 % (1/25)	4 % (1/25)	
Morsy [30]	9.4	10.2	40 % (21/53)	36 % (19/53)	9 % (5/53)	38 % (20/53)		36 % (19/53)	23 % (12/53)
Togrul et al. [29]	14	10.2	14.5 % (9/62)	8 % (5/62)	3.2 % (2/62)	8 % (5/62)		1.6 % (1/62)	
Canale and Bourland [31]			43 % (26/61)			62 % (38/61)		6.5 % (4/61)	
Bagatur and Zorer [36]	6	11	53 % (9/17)	47 % (8/17)		41 % (7/17)		24 % (4/17)	

arthroplasty [3–5]. The choice of treatment depends on skeletal maturity and nature of osteonecrosis [10]. A number of different classification schemes for proximal femoral osteonecrosis have been proposed and utilized, two of which warrant mention. Ratliff et al. proposed a scheme that depended on the region of the proximal femur involved, with type 1 involving the entire head, type 2 being confined to segments of the head, and type 3 involving the femoral neck [1]. The Ficat classification, the original version of which was modified in 1985 [11], categorizes AVN as follows: stage 1 involves a normal radiologic appearance with pain, stage 2 is a transition phase with radiologic changes but no collapse, stage 3 shows a sequestrum with subchondral bone collapse, and stage 4 shows flattening of the femoral head with a decrease joint space. The Kerboul angle can be used to evaluate the size of the necrotic area. It is calculated by adding the angle of necrosis on the anteroposterior view and on the frog view.

If a skeletally mature child presents with early-onset osteonecrosis without collapse, core decompression with or without vascularized or non-vascularized bone graft represents a commonly used approach. A systematic review of 139 cases of core decompression with non-vascularized bone graft reported that 25.8 % went on to total hip arthroplasty for failure of treatment, with the most favorable results in patients with less than 50 % of the femoral head involved [13].

Vascularized bone graft donor site may include from the ipsilateral fibula or iliac crest. A recent meta-analysis showed superior outcomes with fibular vascularized bone graft, compared to other techniques, including iliac vascularized bone graft, non-vascularized bone graft, and core decompression alone. Good to excellent functional outcome measures were 69 % compared to 25 %, respectively, while conversion rate to total hip arthroplasty (16.5 % vs. 42.6 %), collapse rate (16.7 % vs. 63.6 %), and complication rate (23.8 % vs. 8.9 %)—including claw toes, compartment syndrome, sensory peroneal neuropathy, ankle pain, and deep venous thrombosis—all favored fibular vascularized bone graft [14]. Eward et al. reported a series of 65 hips with osteonecrosis in precollapse stage (Ficat stages 1 and 2) that had a fibular vascularized graft. Mean age at time of surgery was 32 years, and mean follow-up time was 14.4 years. At 10 years, 75 % (49/65) had survived the vascularized graft and 60 % (39/65) at the last follow-up. Forty percent (26/65) underwent conversion to total hip arthroplasty at a mean time of 8 years. In that cohort, demographic factors, lesion size, additional procedure, and low preoperative function were not associated to outcome [15].

Vascularized bone grafting is a technically demanding procedure with potentially significant complications, but likely represents a good option for joint preservation at institutions where it is routinely performed. In the presence of a Ficat stage 2 osteonecrosis with partial involvement of the femoral head, Ficat 3, or Ficat 4 AVN, redirectional multiplanar osteotomies may be performed. The objective of this technique is to rotate the necrotic segment out from the weight-bearing area, with the advantage of preserving femoral head and neck and mobility. It is a complex technique and there is a high correlation between the size of the necrotic area and the rate of failure [6]. Different variations of proximal femoral osteotomies can be used to achieve this objective. Sugioka et al. reported excellent outcomes in 78 % of a cohort of 474 hips treated with transtrochanteric rotational osteotomy [17]. Those results have not been reproduced in other studies, with more common rates of good to excellent outcomes in 17–30 % [16, 18, 19].

Other authors have proposed intertrochanteric osteotomy to better preserve blood supply to femoral head. Mont et al. reviewed the long-term outcome of an intertrochanteric proximal corrective osteotomy. At a mean follow-up time of 11.5 years, 76 % had an excellent or good result according to the Harris Hip Score. They identified that the best results were obtained when the combined necrotic angle (Kerboul angle) was less then 200° with good and excellent result in 87 % [20]. Dinulescu et al. reported similar results in 50 hips with a success rate of 70 % at 5 years and 45 % at 10 years [21]. They described statistically significantly better results with the following factors: a preoperative Kerboul angle under 200°, good hip range of motion, and younger age.

When the entire head is involved and has already collapsed, hip fusion or arthroplasty can be considered. Hip arthrodesis is an option for children and adolescents with unilateral hip involvement. One study suggested that the procedure is well tolerated and effective and allows for return to a relatively normal childhood lifestyle [22]. However, other authors have illustrated the longer-term limitations of the procedure. For example, Benaroch et al. reported on a series of 13 male adolescents who underwent hip arthrodesis performed at a mean age of 15.6 years. At a mean follow-up of 6.6 years, ten patients had low back pain and seven had ipsilateral knee pain. Gait laboratory analysis demonstrated abnormal gait parameters (cadence, velocity, and stride length). In order to minimize those complications, they recommend a fusion position at 20° of flexion and 0° of abduction and no more than 2 cm shortening [23]. Many consider hip arthrodesis a temporizing procedure until proper time for hip arthroplasty [24]. Therefore, the surgical approach for arthrodesis should be carefully chosen to preserve hip muscles and bone stock, in order to facilitate a potential eventual conversion to total hip arthroplasty.

Total hip arthroplasty on younger patients has classically been described only in the population of juvenile arthritis patients. However, in recent years, hip arthroplasty has been described more commonly to address a variety of pathologies in increasingly younger patients, with osteonecrosis as the most frequent indication [25]. The classic arthroplasty technique involved use of cemented implants. However, Dorr et al. reported a series of 49 cemented total hip arthroplasty with 16.2 years follow-up in a population between 16 and 45 years, with patients younger than 30 years having a 82 % revision rate, compared to 56 % for patients older than 30 years [26]. Other series have reported revision rates between 8 and 67 % for cemented arthroplasty in young patients (14.6–31.1 years) [25].

In the last one to two decades, use of non-cemented implants has become more prevalent, particularly in the younger population of arthroplasty patients. Restrepo et al. reported on a series of 35 total hip arthroplasty in 25 patients, 46 % of which were secondary to osteonecrosis, with a mean age at time of surgery of 17.6 years and mean follow-up of 6.6 years. The Harris Hip Score improved from 52 preoperatively to 77 postoperatively. There was one case of severe polyethylene wear that required revision [27]. Clohisy et al. reported on a series of 102 hips, 95 % of which were treated with non-cemented implants on a population between 12 and 25 years old at time of surgery (mean 20 years). Mean follow-up was 4.2 years, and the mean Harris Hip Score improved from 43 preoperatively to 83 postoperatively. There were no reported stem revisions, but seven sockets revisions were performed (three dislocations, three polyethylene wear, and one infection) [28]. The reported improvement of outcome scores after total hip arthroplasty supports this treatment as an option for a younger population. The availability of newer, non-cemented implants providing longer fixation and more advanced bearing surfaces, such as highly cross-linked polyethylene and ceramic, has improved the longevity and decreased the revision rate of this approach [25].

Premature Physeal Closure and Growth Disturbance

The prevalence of premature physeal closure associated with pediatric proximal femur fractures varies broadly, with a range between 8 and 62 %, as shown in Table 14.1. Premature physeal closure can be secondary to implant penetration of the physis, to femoral head osteonecrosis, or secondary physeal response to the initial traumatic injury. Togrul et al. concluded from their series that premature physeal closure was most common after pin penetration [29]. Morsy reported a higher incidence of premature physeal closure in patients who had implants through physis, but it was not statistically significant [30]. In a series by Canale and Bourland, 28 patients had physeal penetration by an implant; 5 did *not* develop premature physeal closure. [31]. Other authors found a correlation between premature physeal closure and osteonecrosis, probably from being the result of a higher mechanism of injury [1, 30].

The proximal femoral physis contributes to 13–15 % of the total length of the lower extremity and generates approximately 3 mm/year of growth. Therefore, in a very young child, a complete physeal closure can lead to a significant limb length discrepancy. Usually, limb length discrepancy is defined as any difference of more than 1 cm between the two lower limbs, and when the discrepancy is more than 2 cm it is significant. If the projected discrepancy at skeletal maturity is less than 2 cm, it can be managed with a shoe lift. If projected discrepancy is between 2 and 5 cm, a well-timed epiphysiodesis of distal femur or proximal tibia of the contralateral leg should be planned. Children with premature physeal closure should be followed with full-length lower extremity measurement techniques, such as scanograms. If the proximal femoral physeal injury represents a partial closure on the medial aspect, it can result in coxa vara. If it is a physeal arrest of the greater trochanteric apophysis, it can lead to coxa valga (neck-shaft angle over 150°). On the contrary, overgrowth of the greater trochanteric apophysis can lead to coxa vara. Coxa vara due to fracture will usually undergo remodeling [7].

Nonunion

The prevalence of nonunion has varied in previous reports (see Table 14.1), with Canale reporting 6.5 % [31], compared with Ratliff 10 %, [1], Ingram and Backyniski 8.3 % [32], Kay and Hall 15 % [33], and Morsy et al. 36 % [30]. Fractures at greater risk of developing nonunion are type 2 (transcervical) and 3 (cervicotrochanteric) fractures, those treated in spica cast without rigid fixation, those that are non-anatomically reduced, and those with inadequate or failed fixation [34]. Osteonecrosis can also be associated with nonunion, and if nonunion is suspected, infection should always be ruled out.

Workup of non-union should begin at 3 months post-fracture if the patient is still symptomatic and if no bone bridging is seen on plain radiographs. At that time a computed tomography scan should be performed to evaluate bony bridging. By definition a nonunion is a failure of fracture healing after 4–6 months of treatment. When nonunion is established, infection should be investigated with a basic laboratory workup (CBC with diff, ESR, CRP), and nonunion should be treated operatively. For fractures that had not undergone fixation, rigid implants should be use. The other well-accepted approach is to perform a valgus subtrochanteric osteotomy to allow compression across the fracture site. Systematic bone grafting is not recommended, because of the morbidity of the approach. In all cases, fixation should extend across the site of the nonunion and a spica cast applied, except for older and compliant children and adolescents.

Coxa Vara

Rates of coxa vara, defined as a neck-shaft angle of less than 120°, vary from 3 to 36 % after children hip fracture (Table 14.1). It is the second most frequent complication after pediatric hip fracture. Causes include varus malreduction; loss of reduction; nonunion or delayed union; partial premature physeal closure with overgrowth of greater trochanter; osteonecrosis; or a combination of all those factors [9]. Anatomic reduction with stable fixation is the best way to prevent coxa vara.

As coxa vara progresses, the greater trochanter migrates superiorly, compared to the femoral head, causing a shortening of the extremity and mechanical disadvantage of the abductors. Children under 3 years old with a neck shaft angle of more than 110° have the potential to remodel with future growth [10, 34]. Patients with mild coxa vara and age between 6 and 8 years who present with greater trochanter overgrowth can be manage with greater trochanter physeal closure.

Patients with coxa vara who present with a significant Trendelenburg limp, femoroacetabular impingement from proximal femoral deformation, and/or neck-shaft angle of <110° are candidates for a subtrochanteric valgus corrective osteotomy to restore limb length and abductor strength [9, 35].

Infection

Infection is uncommon after hip fracture in children. Its reported prevalence is low (1 %) and consistent with the expected infection prevalence in any closed fracture treated surgically. Early recognition of infection is important, and prompt intravenous antibiotic treatment should be instituted. An aggressive surgical debridement should be performed, but whenever possible, hardware should be retained until union is achieved.

Chondrolysis

This complication has been reported only in two series [6, 36]. It is usually either associated with osteonecrosis or persistently prominent intra-articular implant. The outcomes of patients with chondrolysis in both series were poor.

Complications of Femoral Shaft Fractures

Femoral diaphysis fracture is one of the most frequent traumatic musculoskeletal injuries in the pediatric population [37]. Complication rates after femoral diaphysis fracture is variable and depends on a complex array of factors, such as the choice of treatment (operative vs. nonoperative), fracture type, and sub-location. For instance, Sink et al. showed a decrease in complication rate from 53 to 23 %, after limiting the use of titanium elastic nails to unstable fracture pattern [38]. Another example is a study by Keeler et al. on rigid intramedullary nailing, in which the authors reported no complication at a mean time of 8-year follow-up in a group of 78 patients (mean age 12.6 years at time of surgery) [39]. Optimal primary treatment of pediatric diaphyseal femur fractures, particularly in the middle age-group of "school-age" children, or those 5–12 years old, remains an area of controversy that requires continued study. The current section will review the management of some of the different established complications, independent of considerations toward the initial management of the fracture.

Malunion

The diagnostic criteria needed to establish the presence and severity of rotational deformities of the femur, and the accuracy of those measurements, is somewhat controversial. While plain radiographs are generally not accurate, computed tomographic (CT) scanning remains the gold standard of assessment [40]. The degree of rotational deformity that is well tolerated in the femur is between 10 and 30°, depending on the preexisting anteversion or retroversion. Obviously, prevention of this complication is more straightforward than its management after the fact, and requires performing an anatomic initial reduction in the axial plane. Rotational malreduction can be evaluated preoperatively with the cortical step sign [41]. This represents an incongruity of the cortex width on either side of the fracture, which usually represents either internal or external malrotation. Definition of angular deformity malunion is somewhat age-dependent. Before 2 years old, 30–40° of flexion/extension, 10–15° of varus, and 20–30° of valgus, are considered acceptable. For older children and adolescents, flexion/extension deformation up to 15° and varus/valgus to 10° may be reasonable. Remodeling occurs best in the direction of motion at the adjacent joint, which is flexion/extension in the knee; therefore varus/valgus deformities are more likely to cause problems than flexion/extension deformity [42].

Angular deformities may occur with closed reduction and spica casting, but also, as recently published, in the long-term follow-up of certain forms of surgical treatment. Heyworth et al. reported that distal femoral valgus deformity occurs in 12 % of a series of 85 diaphyseal femoral fractures fixed with submuscular plating, a rate that increased to 30 % when the fracture was located in the distal third of the femoral diaphysis [43]. Anterior bowing greater than 15° was reported as a common malunion following titanium elastic nails fixation of pediatric femur fracture [44].

When union is achieved and a significant angular deformity exists, a period of observation for a minimum of 1 year is generally pursued to evaluate the natural effect of remodeling. If after 1 year a persistent impairment of function and abnormal appearance of the leg exists, a corrective osteotomy can be considered. This should be performed at the level of the fracture site and stabilize with rigid fixation.

Delayed Union and Nonunion

Time required for union of femoral shaft fractures in children and adolescent varies with age from 4 to 6 weeks before 5 years of age, to 13–15 weeks over 15 years of age [45]. Delayed union and non-union are rare in pediatric femoral shaft fracture. When signs of delayed healing arise, the cause is either biologic, mechanical, or both. Although rare, among the most common biologic causes is infection, which should be treated as soon as possible with intravenous antibiotics and surgical debridement. Mechanical causes include distraction at the fracture site by rigid fixation, which has been described for plates (Fig. 14.1a–e), intramedullary nail, and external fixator constructs. If a gap exist in fracture site that precludes bony healing, the fixation should be revised with a load-sharing implant and compression at fracture site, with or without bone grafting. If associated with external fixation, the stability might be suboptimal for healing and this often arises as a hypertrophic non-union. A revision with rigid fixation and possible bone grafting is recommended.

Compartment Syndrome

Compartment syndrome of the thigh is very rare but has been reported in patients who have sustained high-energy injury with massive swelling [46]. When a patient with a stabilized femur fracture complains about increasing pain, thigh compartment pressure should be measured. A pressure over 30 mm of Hg is diagnosis of compartment syndrome and early fasciotomies should be performed.

An important contribution by Mubarak et al. [8] reported on nine cases of compartment syndrome, Volkmann's contractures, and anterior ankle skin loss following spica cast application for low-energy femur fractures. The authors proposed a mechanism in which the preliminary application of a short leg cast, used to facilitate a traction reduction maneuver for the distal fracture fragment, followed by completion of the cast through the femur region, generated dangerous sites of focal pressure in the popliteal fossa and dorsum of the ankle. They recommend *against* use of this specific sequence in “90/90 spica casting,” and propose an alternative set of steps for the positioning, reduction, and molding of the cast to avoid this devastating complication.

Leg-Length Discrepancy and Growth Disturbance

Leg-length discrepancy is the single most frequent complication after pediatric femoral fracture. Shortening is seen initially with overriding of the fracture fragments (Fig. 14.2a–d), whereas growth acceleration occurs in the remodeling phase, and overgrowth is seen on a delayed basis. Overgrowth is more likely in children between 2 and 10 years old, while shortening is more likely in patients older than 10 years [47]. Shapiro reported a mean overgrowth of 0.92 cm (0.4–2.7) in a cohort of 74 patients younger than 13 years with a femoral shaft fracture. Overgrowth was independent of age and level of fracture, with 78 % of the overgrowth occurring in the first 18 months after the fracture [48]. Park et al. reported on overgrowth risk factors after titanium elastic nailing in a series of 43 patients with a mean age of 7.1 years (3.6–12 years). At a mean follow-up of 40.3 months, 25.6 % of children had developed overgrowth of more than 1 cm. The only significant risk factor was the nail-canal diameter ratios; a lower ratio

Fig. 14.1 (**a**) Preoperative radiographic image of an 8-year-old male with a right femur fracture. AP (**b**) and lateral (**c**) views following open reduction internal fixation. (**d**, **e**) Hypertrophic nonunion at 6 months post-op

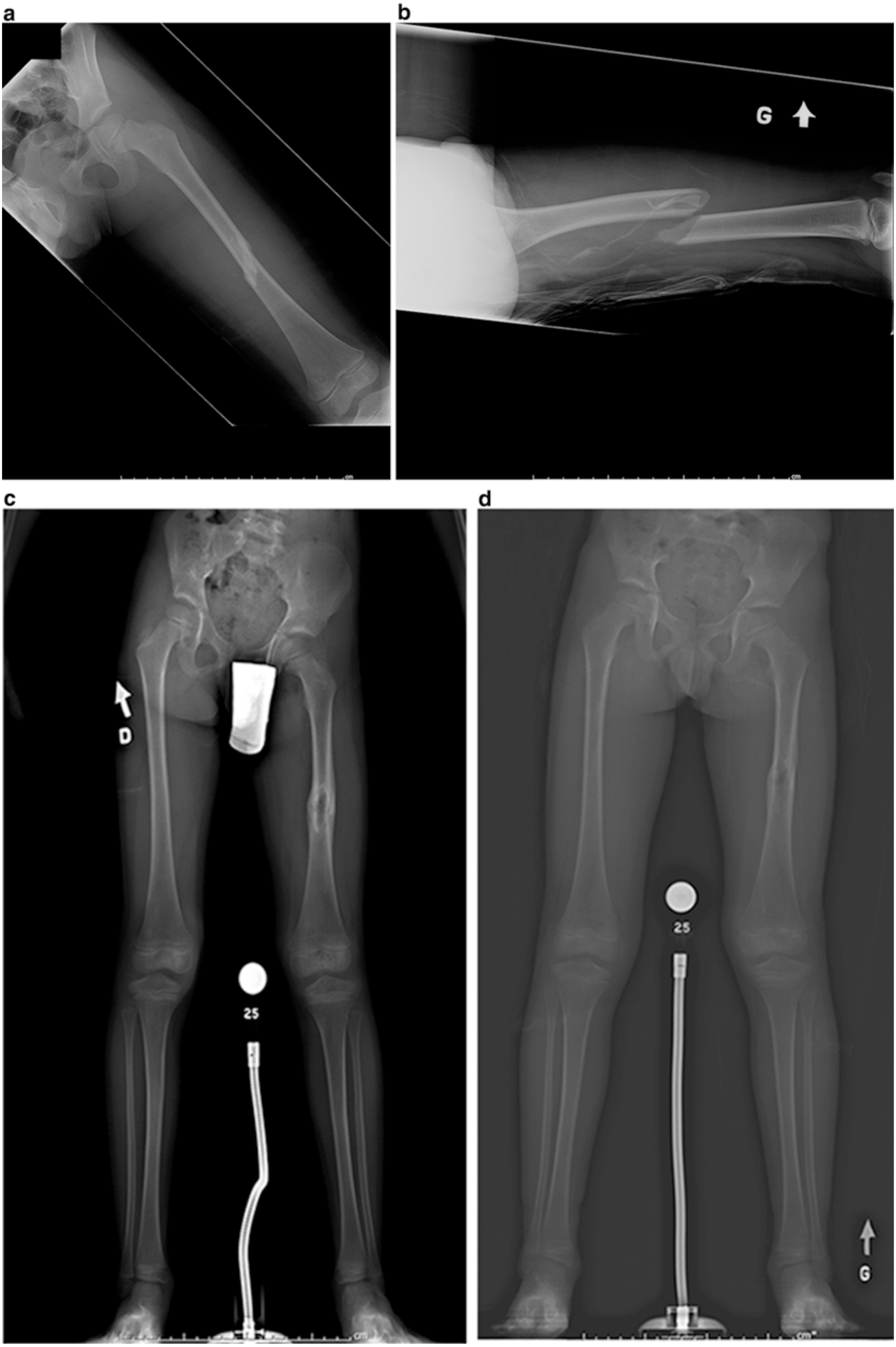

Fig. 14.2 (**a**, **b**) Injury radiographic images of a 5-year-old male with a right femur fracture. Treated with traction for 2 weeks followed by 6 weeks in spica cast. (**c**) Six-month follow-up X-ray. (**d**) At 1-year follow-up there is a 24 mm shortening of the right femur

was associated to a significant increase risk of overgrowth, which they concluded related to less fracture stability [49]. Within 2 years after injury, overgrowth generally stabilizes [50] and a realistic measurement of the leg length discrepancy can be assessed. A well-planned ipsilateral epiphysiodesis can be performed in order to correct the discrepancy. If not enough growth remains, ipsilateral femoral shortening of contralateral lengthening procedure can be considered.

Shortening is an early complication seen either after closed reduction and spica casting or, more rarely, after failed internal fixation associated with an unstable fracture pattern. Management depends on the age of the patient and the amount of shortening. In a patient approaching skeletal maturity, a maximum of 1–2 cm shortening should be accepted, given that this is likely to approximate the final leg-length discrepancy. In this age group, however, a discrepancy >2 cm may be the result of failed internal fixation; in such cases revision surgery should include closed or opened reduction with rigid fixation. For example, shortening of an unstable mid-diaphyseal femur fracture treated with titanium elastic nails in a 14-year-old boy could be revised with rigid intramedullary nailing or submuscular plating. If the unacceptable shortening is documented later than 6 weeks post-fracture, an early revision with closed or opened callus osteoclasis and multiplanar external fixator should be considered [51]. The other option is to allow the fracture to heal in a shortened position if there is no angular or rotational malalignment and plan for later epiphysiodesis or lengthening.

For patients between 2 and 10 years old, an average of 1–1.5 cm overgrowth may be expected, so a shortening of up to 2 cm at the time of casting, but no more than 3 cm at final healing, is generally considered acceptable in the cast. If a shortening of more than 2 cm is measured at the time of the closed reduction, spica cast revision should be performed, underscoring the benefit of confirmatory radiographs while the patient is still under anesthesia. If initial closed reduction and spica cast failed, other option is to consider internal fixation with flexible nails, particularly in school-aged children.

Muscle Weakness

Hennrikus et al. [52] reported a surprisingly high prevalence of quadriceps weakness and atrophy in a cohort of 33 patients who were treated for femoral shaft fracture before 17 years old. At a mean of 33 months (range 18–56 months) post-injury, 39 % had persistent decreased in quadriceps strength on Cybex dynamometer evaluation, and 42 % had more than 1 cm decreased in thigh circumference. Even though differences were found with dynamometer evaluation and thigh circumference, none of the patients reported clinically significant functional limitations at the last follow-up. Finsen et al. [53] reported on a cohort of plated (12 patients) and nailed (14 patients) femoral shaft fractures and found moderate quadriceps muscle weakness in the plated group and hamstrings weakness in both groups. Analysis showed that the interval between fracture and strength evaluation correlates with hamstrings strength in the nailed group. Hedin and Larsson [54] reported a case-control study on muscle strength between a group of femoral shaft fracture treated with external fixation and an age-, sex-, and weight-matched control group. They found no difference in muscle strength with hop-index test and Cybex testing between unfractured and fractured extremities or between subject and controls. Physical therapy with transition to a more long-term, home-strengthening program is likely to be effective as treatment for this somewhat underappreciated but minor complication of pediatric femur fractures.

Neurovascular Injury

Neurologic and vascular injuries are uncommon with pediatric femur fracture. Vascular injury prevalence is around 1.3 % of all femoral fracture in children, including intimal tears, pseudoaneurysms and total disruption [55–57]. Because vascular injuries are more common with distal metaphyseal fractures, discussion of management of vascular injuries will be included in section “Complications of Distal Femoral Fractures” of this chapter.

Nerve injuries associated with femoral shaft fracture are either the result of direct trauma (most commonly sciatic and femoral nerve) or occur during treatment (most commonly peroneal nerve). If injury to sciatic or femoral nerve is detected at presentation of a closed femoral fracture, no exploration of the nerve is required and a spontaneous recovery is expected. If no sign of recovery is seen persisting after 3 [months/weeks?], further investigation should be performed, such as MRI and EMG, with possible nerve exploration if warranted by the findings of the other diagnostic studies. Peroneal nerve injury has been described in association with early 90/90 hip spica casting [58], with delayed locked intramedullary rodding, and with traction [59]. Whereas, following femoral and sciatic neuropraxias, spontaneous recovery is expected, peroneal nerve injuries have a variable course; therefore a dorsiflexion brace should be used to prevent Achilles contractures, which is particularly important in rapid growing children.

Infection

Infection is a rare complication of pediatric femoral shaft fractures. The classically reported scenario for this complication is pin-track infection associated with skeletal traction. It is usually superficial and treated with local wound care and antibiotic therapy. More significant deep infections are addressed with standard principles.

Complications of Distal Femoral Fractures

Growth Disturbance

Distal femoral physeal fracture is associated with a relatively high rate of physeal arrest, ranging from 27 to 90 % [60]. Basener et al. published a meta-analysis of 16 studies with 564 patients and reported a prevalence of 52 % of growth disturbance after a distal femur physeal fracture [61]. This physeal arrest can result in angular deformity, leg-length discrepancy, or both (Table 14.2).

Physeal bars are generally appreciable on routine radiographs by 6 months post-fracture in the form of a frankosseous bridge, thinning of the physeal line, or nonparallel Park-Harris growth arrest lines. The treatment of physeal arrest is defined according to age of the patient and size of the bar. The gold standard exam to evaluate the bar size is MRI [62]. Excision of the bar is recommended if the bar represents less than 25–50 % of the total area of the physis with at least 2 years of growth remaining [63]. If the angular deformity is over 20°, a simultaneous corrective osteotomy should be considered if hemiepiphysiodesis and application of guided growth principles are unlikely to achieve gradual correction [64]. Several different series show a high rate of failure of bar resection procedure with more than 50 % of the physis involved, with recurrence of the bar and limited achievement of physeal growth reported [65, 66]. In older adolescents who are

Table 14.2 Complications of fractures of the distal femoral epiphysis

Study	Mean age (years)	Mean follow-up	Neurovascular	Ligamentous	Angular deformity	Shortening	Stiffness
Eid and Hafez [70]	12.3	8.2 years	2.6 % (4/151) vascular 7.3 % (11/151) peroneal nerve	13.9 % (21/151)	50.9 % (77/151)	38.4 % (58/151)	28.5 % (43/151)
Garrett et al. [60]	10 (median)	2 years minimum			21.8 % (12/55)		
Basener et al. [61]		1 year minimum			52 % (291/564) overall growth disturbance	22 % (112/506) (more than 1.5 cm)	

nearing skeletal maturity, an epiphysiodesis and contralateral epiphysiodesis is suggested.

If bar excision fails and leg-length discrepancy progress with more than 2 cm discrepancy at maturity is predicted, epiphysiodesis and contralateral epiphysiodesis can be done [67]. This procedure or a leg-length discrepancy of more than 2 cm was required in 10–50 % of patients, depending on the series [68, 69]. Angular deformity can be treated with hemiepiphysiodesis or osteotomy. In adolescents with minimal growth remaining, osteotomy is preferred. In maturing adolescents with progressive angular deformity, a hemiepiphysiodesis can be considered, especially with a more central bar and remaining growth laterally or medially. If hemiepiphysiodesis fails and an unacceptable angulation exist at skeletal maturity, then an osteotomy can be done.

Ligamentous Injuries

The best way to minimize complications associated with ligamentous injuries is to meticulously test knee stability after fixation and again after the fracture is healed, but before allowing the patient to return to regular activities or more aggressive rehabilitation. If ligamentous injury is suspected, an MRI of the knee should be obtained. If an anterior cruciate ligament tear is associated to the distal femoral fracture, it should be treated in standard fashion after both fracture healing *and* a near-normal range of motion have been achieved [69]. Eid et al. [70] reported 13.9 % of knees demonstrated ligamentous laxity after fixation in his series of 151 patients, but only 7.9 % were symptomatic. Advanced imaging revealed the following rates of ligamentous injuries: anterior cruciate ligament 7.3 % ($n=11$), medial collateral ligament 2.6 % ($n=4$), and lateral collateral ligament 4.0 % ($n=6$) (Table 14.2).

Vascular Injuries

Vascular injuries of the lower extremity are most commonly seen with proximal tibial fractures, but when associated with femoral fractures, most frequently involves the distal femur. It is important to keep in mind that a fracture that appears minimally displaced at presentation might have had significantly more displacement at the time of injury, and a careful monitoring should be done for all distal femoral fractures. Assessment of vascular status with peripheral pulses and, if abnormal or questionable, with the addition of ankle-brachial indexes performed at the time of presentation, after reduction and fixation. If abnormal pulses and ABIs are detected, an angiography is recommended. If vascular repair is necessary, consideration should be given towards use of temporary stabilization with external fixation (Table 14.2).

Stiffness

Stiffness after a distal femoral fracture can be caused by intra-articular adhesions, capsular contracture, or muscular contracture. Usually the first step in management is aggressive physical therapy involving active, active-assistive range of motion, with or without the addition of a dynamic brace. If conservative treatment fails, an arthroscopic lysis of adhesions, manipulation under anesthesia, surgical tendon lengthening (more rarely needed), or some combination of the three can be performed with a continuous passive motion machine utilized in the early postoperative phase [71] (Table 14.2).

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