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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

J. Phillips, MD (✉)
Orlando Health/Arnold Palmer Hospital for Children,
1222 S. Orange Avenue, 5th Floor, Orlando,
FL 32806, USA
e-mail: jonathan.phillips@orlandohealth.com

D.D. Spence, MD
Department of Orthopaedic Surgery, University of
Tennessee/Campbell Clinic, 7545 Airways Blvd.,
Southaven, MS 38671, USA

D.M. Kelly, MD
Department of Sports Medicine and Shoulder
Surgery, Hospital for Special Surgery,
541 East 71st Street, New York, NY 10021, USA

D.J. Hedequist, B.E. Heyworth (eds.), *Pediatric Femur Fractures*,
DOI 10.1007/978-1-4899-7986-5_11

Fig. 11.1 Fracture after external fixation

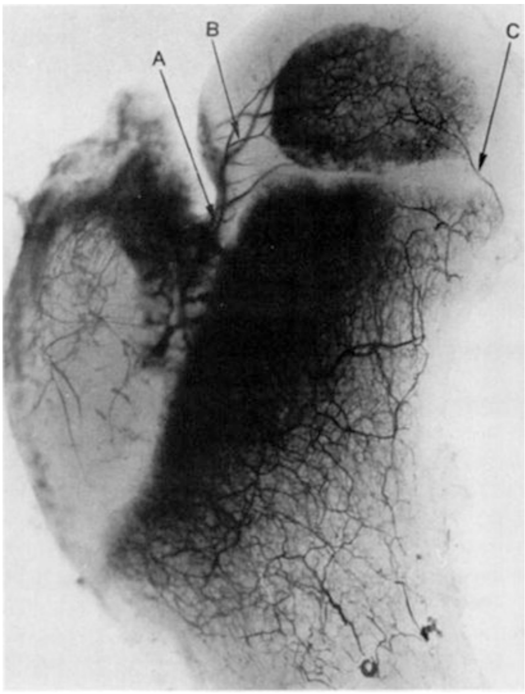

Fig. 11.2 The lateral epiphyseal artery is labeled *B* in this radiograph. Reprinted with permission from Journal of Bone and Joint Surgery Amercian, 1976, 58, The arterial supply of the developing proximal end of the human femur, Chung, 961–970

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

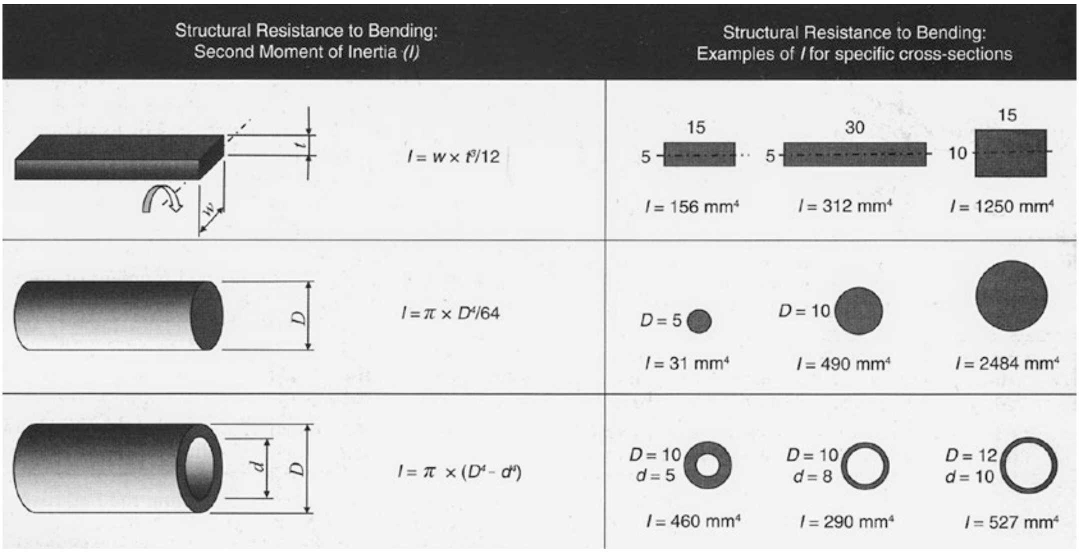

Fig. 11.3 Influence of cross-sectional geometry on bending stiffness of basic structures, e.g., increasing the outer diameter of a cylindrical structure from 10 to 12 mm while retaining a wall thickness of 2 mm increases bending stiffness (*I*) by 82 %. Reprinted with permission from Bottlang M, Fitzpatrick 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

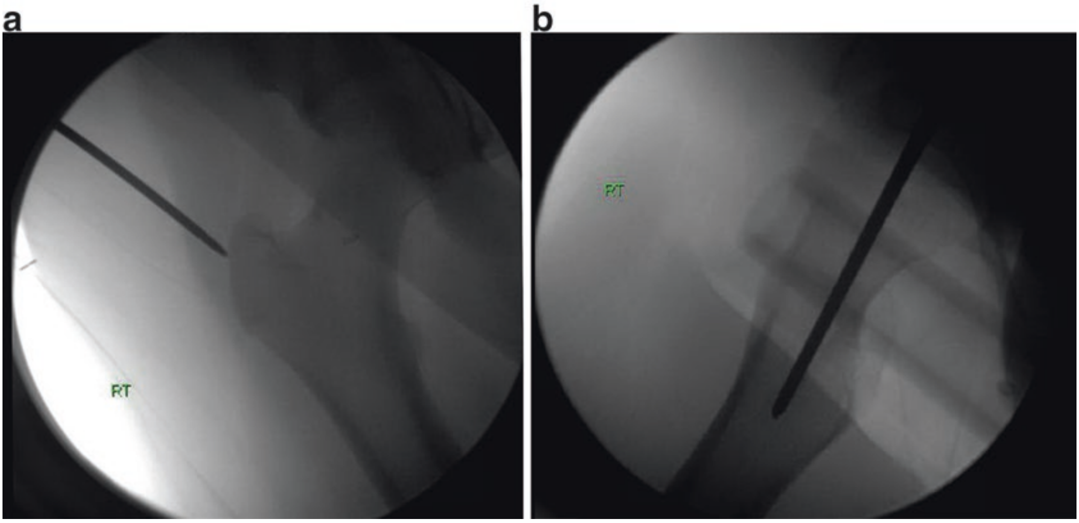

Fig. 11.5 (**a**, **b**) Positioning the guidewire

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.

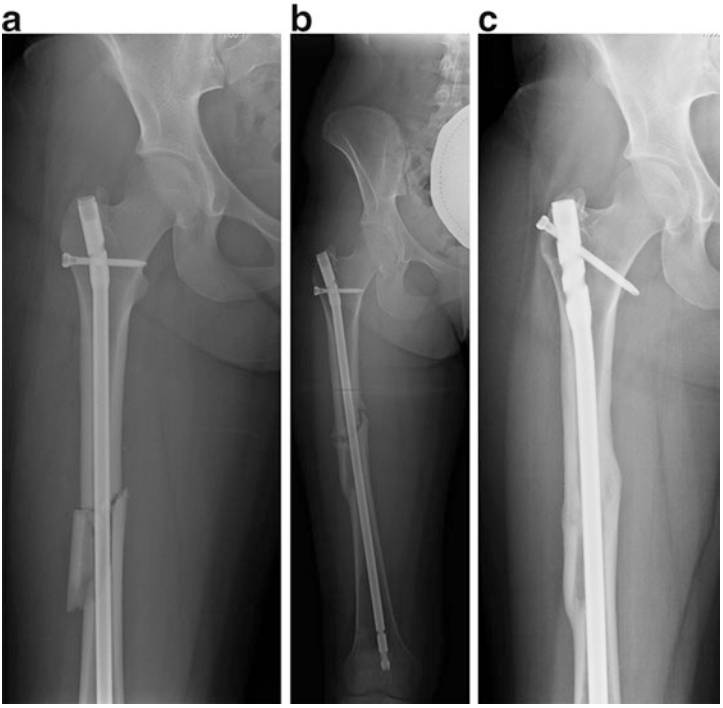

Fig. 11.7 (**a**–**c**) Exchange femoral nailing in nonunion. (**a**) Nonunion of femoral shaft fracture. (**b**) Postoperative radiograph of exchanged nail. (**c**) Healed fracture

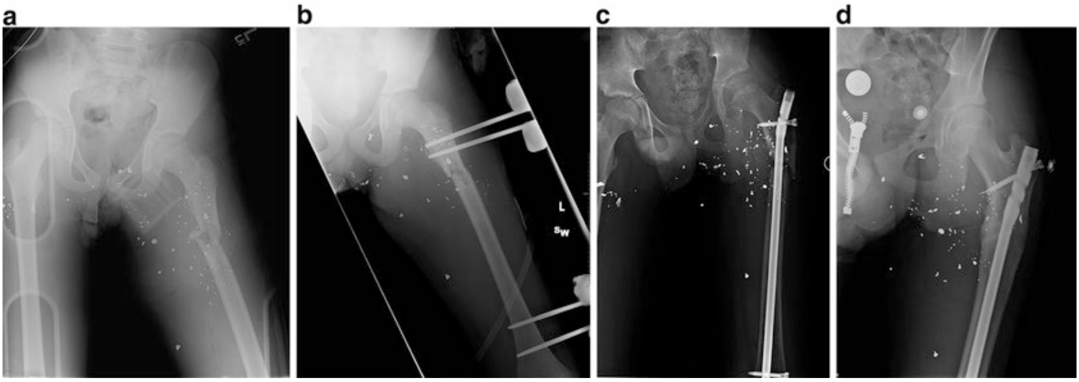

Fig. 11.8 (**a**) Proximal femoral shaft fractured caused by gunshot. (**b**) Treated with external fixation. (**c**) Nonunion developed, and the patient was treated with intramedullary nailing. (**d**) Radiograph reveals fracture healing

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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