Intramedullary Nailing of Pediatric Femoral Shaft Fracture

Abstract

Intramedullary nail fixation of pediatric long bone fracture, particularly femoral shaft fracture, has revolutionized the care and outcome of these complex injuries. Nailing is associated with a high rate of union and a low rate of complications. Improved understanding of proximal femoral vascularity has led to changes in nail insertion methodology. Multiple fixation devices are available; selection is based on fracture type, patient age, skeletal maturity, and body mass index. A thorough knowledge of anatomy and biomechanics is required to achieve optimal results without negatively affecting skeletal development.

Femoral shaft fracture is among the most common reasons for inpatient admission; estimated annual incidence is 19.5 per 100,000 children.1–3 Multiple treatment modalities are available, including Pavlik harness, spica cast, skeletal traction, external fixation, submuscular plating, flexible intramedullary (IM) nailing, and rigid trochanteric entry IM nailing. Factors to consider in determining treatment include patient age, weight, skeletal maturity, social situation (ie, involvement of caregivers, child abuse), fracture location, mechanism of injury, and the presence of concomitant injuries.

In 2009, the American Academy of Orthopaedic Surgeons (AAOS) released a clinical practice guideline on the management of pediatric diaphyseal femoral fracture.4 In patients aged ≤6 months, treatment with a Pavlik harness or spica cast is an option. However, spica casting is associated with an increased incidence of skin breakdown.5 The AAOS guideline suggests performing early spica casting in children aged 6 months to 5 years with diaphyseal femoral fractures demonstrating <2 cm of shortening on initial postinjury radiographs. Flexible IM nailing is recognized as a treatment option in children aged 5 to 11 years. Proposed advantages of flexible nailing compared with spica casting and external fixation are shorter time to weight bearing (as tolerated) and return to activity.6–8 Rigid trochanteric entry nailing, submuscular plating, and flexible IM nailing are options in patients aged ≥11 years; however, no studies have directly compared all three treatment methods. The AAOS work group noted a lack of high-quality evidence regarding the use of these devices. As use of these devices increases, it is imperative to determine the role of IM fixation in managing pediatric femoral shaft fracture.

Anatomic and Biologic Considerations

Vascular Anatomy

Understanding of femoral head vascularity, as well as the anatomy of the hip joint and capsular structures, has been clarified by the extensive...
work of Ganz and colleagues. Blood supply to the femoral head is delivered by the deep branch of the medial femoral circumflex artery (MFCA). This branch divides into two to four superior retinacular vessels and, in some cases, inferior retinacular vessels (Figure 1). The MFCA is composed of five branches: superficial, ascending, acetabular, descending, and deep. The primary partition of the deep branch traverses posterior to the obturator externus tendon and anterior to the superior gemellus, obturator internus, and inferior gemellus tendons. The MFCA has two central and five peripheral anastomoses. The peripheral anastomoses are extracapsular; the largest branch is located along the inferior border of the piriformis. Damage to these branches can have a disastrous effect on the developing femoral head (eg, osteonecrosis, collapse). Therefore, these branches must be left intact to prevent iatrogenic complications and disability. Kalhor et al demonstrated that the hip capsule also receives contributions from the medial and lateral circumflex arteries distally and the superior and inferior gluteal arteries proximally. Because these branches of the MFCA are close to the piriformis fossa, the use of nails with a piriformis starting point is associated with a risk of proximal femoral osteonecrosis in the pediatric population.

Rhinelander demonstrated in an animal model that the femoral blood supply is two thirds endosteal and one third periosteal. The normal direction of blood flow is centrifugal (ie, from the center outward). In Rhinelander's study, disruption of endosteal vascularity resulted in centripetal blood flow.

**Femoral Growth**

Understanding femoral remodeling potential and vascularity in relation to femoral growth in the pediatric population is essential when considering IM nailing for the management of...
of femoral shaft fracture. Most femoral growth occurs at the distal femoral physis, at a rate of approximately 10 mm per year.\textsuperscript{16,17} In contrast, the proximal femoral physis contributes <4 mm of growth per year.\textsuperscript{16,17} Injury to the distal and proximal physes could cause growth arrest and angular deformity and thus must be avoided. In children and adolescents, IM nailing is predicated on physeal avoidance, particularly when selecting the nail entry point (Figure 2).

**Trochanteric Growth**

To avoid osteonecrosis in skeletally immature patients, the IM nail should be started at the tip of the greater trochanter rather than at the piriformis fossa, away from the arterial supply. However, insertion of the nail through the tip of the greater trochanter carries the risk of proximal femoral valgus, femoral neck narrowing, and greater trochanteric physeal arrest.\textsuperscript{18-20} At birth, the proximal femoral physis is combined, consisting of both the femoral head and the greater trochanter. Between ages 1 and 4 years, a split occurs in this growth zone, with delineation of the femoral head, physis, and trochanteric apophysis.\textsuperscript{21,22} It is believed that a portion of the physis remains along the lateral aspect of the femoral neck after the split.\textsuperscript{23} Damage to this growth zone can occur during nailing through the tip of the trochanter, which may lead to complications.\textsuperscript{19} Current fixation techniques favor a lateral trochanteric entry point, which avoids the risk of proximal femoral deformity and osteonecrosis (Figure 3).

**Surgical Timing**

In contrast to adult patients, no consensus exists regarding optimal timing of femoral shaft fracture fixation in pediatric patients with polytrauma. Loder\textsuperscript{24} reported that pediatric polytrauma patients who underwent early fracture stabilization (≤72 hours postinjury) required shorter stays in intensive care and in the hospital as well as decreased time on ventilator support. In contrast, Hedequist et al\textsuperscript{25} reported that timing of fracture stabilization did not appear to affect the prevalence of pulmonary complications in pediatric trauma patients.

We believe that definitive fixation (ie, IM nailing) should be performed in the pediatric polytrauma patient who is medically stable. Temporary stabilization (eg, external fixation,
traction) is used in patients who are not sufficiently stable to undergo definitive fixation. Conversion to IM nailing from external fixation is safe; however, it should be performed within 2 weeks of injury to avoid complications (eg, infection).26

Surgical timing of definitive fixation of open femoral shaft fractures in the pediatric population remains controversial. In a retrospective multicenter study of 554 open pediatric fractures, Skaggs et al27 noted that the rate of acute infection was similar regardless whether surgery was performed within 6 hours or ≥7 hours after injury (3% versus 2%, respectively). However, only 37 of the 554 fractures were open femoral fractures, and the authors did not indicate how many of those were diaphyseal. Based on these data, it is difficult to draw clinically significant conclusions regarding the timing of surgical fixation of open femoral shaft fractures. Timing of surgical fixation should be individualized based on sound clinical judgment following thorough patient evaluation.

Vascular injury in combination with femoral shaft fracture is rare in the pediatric population.28 Immediate surgical intervention in consultation with a vascular surgeon is recommended in the patient with suspected vascular injury.

**Biomechanics of Flexible Nailing**

**Material Considerations**

Steel is a stiffer material than titanium (modulus of elasticity, 200 and 110 GPa, respectively).29,31 Although titanium has greater flexibility than steel, titanium IM nails have been shown to provide better biomechanical stability than stainless steel nails in torsion and axial compression.29,32 Titanium nails also provide better gap closure and decreased nail slip.

Axial compression stiffness was found to be substantially greater with titanium nails than with steel nails (approximately 900 N/mm and 500 N/mm, respectively).29 At distal femoral insertion sites, steel nails fail under an axial compressive force of only 185 N, which corresponds to approximately 40% of the body weight of a child weighing 45 kg.33 The better biomechanical stability offered by titanium may be due to its greater flexibility, which results in a lower stress level and increased contact with the canal walls.32

In contrast, Wall et al34 reported better clinical outcomes with stainless steel elastic nails than with titanium elastic nails in children with femoral fracture. Fifty-six children were treated with titanium elastic nails, and 58 were treated with stainless steel elastic nails. Children in the titanium nail group had a malunion rate nearly four times that of children in the stainless steel nail group (23.2% and 6.3%, respectively). The rate of major complications (eg, nail irritation requiring revision surgery, infection, delayed union, rod breakage) was higher in the titanium nail group than in the stainless steel nail group (35.7% and 16.7%, respectively). Based on these findings, in addition to the lower cost of stainless steel nails, the authors concluded that stainless steel nails are clinically superior to titanium nails. There is no consensus in the literature regarding which type of elastic nail is clinically superior, and pediatric femoral shaft fractures continue to be managed successfully with both types of nail.

**Nail Dimensions**

Factors to consider when selecting the type and number of nails needed to maximize stability include biomechanical properties, ease of use, ability to achieve fracture reduction, and restoration of rotational alignment. Various nail diameter combinations and asymmetric combinations of nails have been studied. A three-nail configuration has been evaluated, as well. The authors of a biomechanical study of flexible IM nails reported that combinations of single nails with diameters measuring >40% of the canal width prevented fracture reduction and resulted in posterior gapping.35 The use of two nails with a combined diameter equal to 80% of the IM canal at its narrowest width has been recommended.36,37 Typically, surgeons are taught to use two flexible nails of identical diameter for fracture fixation. Although combinations of large-diameter nails (ie, >40% of the canal width) can result in greater stiffness, they present an increased risk of fracture malreduction, posterior gapping, and rotational malalignment.38

**Biomechanical Properties**

Poor clinical outcomes have been reported in patients weighing >49 kg who underwent femoral shaft fracture fixation with titanium nails.36,38 In one study, increased sagittal angulation was related to patient weight and the diameter of the implanted titanium elastic nails.36 Moroz et al38 reported similar results, indicating a correlation between poor outcome and age ≥11 years and weight >49 kg.

Biomechanical studies support clinical findings that titanium elastic nails should not be used in patients weighing >40 to 45 kg. Loads of approximately ≥600 N lead to structural sagittal and coronal deformation of the nails caused by loss of fracture reduction in those planes.39 We prefer to use titanium nails for patients aged <11 years who weigh <45 kg. In patients aged <11 years who weigh >45 kg, we use stainless steel flexible nails.
Antegrade Versus Retrograde Stabilization

Fricka et al. noted that antegrade stabilization of mid diaphyseal fracture with one C-shaped and one S-shaped nail demonstrated 69% greater load at 5 mm of compression than did retrograde stabilization with two C-shaped nails (417 N and 247 N, respectively). These forces correspond to 95% and 55%, respectively, of the body weight of a child weighing 45 kg. However, retrograde fixation of mid diaphyseal fractures provides significantly higher torsional and bending stiffness than does antegrade nailing (350 ± 72 N/mm and 195 ± 95 N/mm, respectively; \( P = 0.02 \)).

In biomechanical studies, retrograde nailing has been shown to be less stable than antegrade nailing in resisting shortening. When maximal axial stability is required, proximal insertion of C- or S-shaped nails is recommended. Retrograde insertion is routinely used for elastic nail insertion because it is technically easier than antegrade nailing. Additionally, it provides better torsional stability and greater surgeon comfort because fewer vital structures are located in the area of surgical dissection.

Flexible Nailing

Compared with external fixation of closed fractures, flexible nailing is associated with decreased time to full weight bearing, full range of motion (ROM), and return to school; in addition, flexible nailing is associated with a lower incidence of complications (eg, pain, limb-length discrepancy, malalignment). Salem and Keppler prospectively studied 68 children who underwent elastic stable IM nailing for unilateral femoral shaft fracture to evaluate for early angular or rotational malalignment and limb-length discrepancy (mean age, 5.6 years; average weight, 21 kg). The authors concluded that elastic stable nailing can provide satisfactory results in terms of limb length and axial alignment. However, in 32 children, they noted a high rate of torsional malalignment (≥15°). External fixation is an option in medically unstable patients and in patients with extensive soft-tissue injuries and/or neurovascular injuries that require repair or reconstruction. We recommend flexible nailing in children aged 5 to 11 years.

Our preferred technique is retrograde titanium elastic nailing with the patient in a supine position on a radiolucent flat-top operating table. The procedure can be performed on a fracture table, as well. Prior to prepping, the patient’s position is adjusted to allow adequate space for the image intensifier. The leg is held elevated off the table and prepped in the standard fashion from the iliac crest to the toes. We prefer to use a radiolucent triangle for knee flexion and ease of fracture reduction. Alternatively, a bolster or a bump may be used.

The starting point is approximately 2.5 cm above the distal femoral physis. Deep dissection in the area of the distal femoral physis should be avoided to decrease the chance of growth arrest. Deep posterior dissection should be avoided to prevent injury to the posterior neurovascular structures. The entry point may be made with a drill bit and a drill guide sleeve to protect the soft tissues. The tip of the nail is sharp enough to negotiate the bone in the area of the metaphysis. Medial and lateral nails are inserted at the same level in the AP and lateral planes. Both nails should be introduced up to the fracture site, but short of the fracture line.

Fracture reduction is performed with appropriate maneuvering (ie, knee flexion, traction, muscle relaxation) and the use of an F-shaped reduction device (ie, F tool), if necessary. Close attention should be paid to rotational and angular alignment. One at a time, titanium elastic nails are advanced beyond the fracture site. Nails are rotated such that the concavities face each other and remain symmetric. In slightly proximal diaphyseal fractures, better torsional and rotational stability can be achieved when one nail is progressed into the region of the inferior neck and the other into the trochanter. Only 1 to 1.5 cm of the nail should remain outside the bone. End caps may be used. To avoid soft-tissue irritation, the nail tip should not be
bent away from the metaphysis. Rotational stability and good cortical apposition should be confirmed prior to leaving the operating room. A knee immobilizer or cast may be required for additional stability.

**Rigid Nailing**

Flexible nailing must be done carefully in patients aged >11 years who weigh >49 kg and who present with very proximal and/or very distal fractures and/or unstable comminuted or long oblique fracture patterns (Figure 5). In these cases, either flexible nailing should be supplemented with adjunctive bracing, casting, or prolonged immobilization, or an alternative fixation device (eg, rigid trochanteric entry nail) should be inserted.

No study has compared rigid trochanteric entry nailing with flexible nailing. We believe that regardless whether a patient has an unstable comminuted or oblique fracture, rigid nails are appropriate for patients aged >11 years who weigh >49 kg. We recommend the lateral trochanteric approach to avoid the risks associated with starting at or near the piriformis and near the tip of the trochanter. Keeler et al reported excellent results in a retrospective review of 78 patients (80 fractures) treated with IM nail fixation through the lateral aspect of the greater trochanter. Keeler et al reported excellent results in a retrospective review of 78 patients (80 fractures) treated with IM nail fixation through the lateral aspect of the greater trochanter. Keeler et al reported excellent results in a retrospective review of 78 patients (80 fractures) treated with IM nail fixation through the lateral aspect of the greater trochanter.

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High-quality data are lacking regarding pediatric patient positioning and the type of table required for optimal femoral shaft fracture fixation with rigid nails, but translational studies from the adult literature are instructive. A fracture table affords the surgeon the ability to perform the procedure with fewer assistants, and it allows circumferential access to the leg. Disadvantages associated with the use of a fracture table include the risk of compartment syndrome of the well leg and increased risk of rotational malalignment resulting from limited access to the contralateral leg. These complications, particularly internal rotational malalignment, can be avoided with the use of a radiolucent table; surgical time can be reduced, as well.

Supine versus lateral patient positioning on a radiolucent table has also been studied. Physician preference is a significant factor in determining patient positioning. However, the surgeon should have knowledge of both positioning techniques because patient factors may preclude the use of one or the other. Advantages of the supine position include ease of patient positioning and administration of anesthesia. Additionally, rotational malalignment of the distal fragment is more easily identified with the patient supine. Accurate identification of the entry point and proximal insertion of instrumentation can be challenging, particularly in patients with a high body mass index (eg, >30). Lateral positioning offers improved access to the trochanteric starting point, particularly in obese patients. This allows access to the limb from both sides and easier lateral imaging of the femoral head and neck (Figure 6). The lateral trochanteric starting point is in a more accessible location, which may make pediatric rigid nail insertion easier (Figure 7). The senior author (H.S.H.) prefers to perform femoral nailing on a radiolucent flat-top table with the patient in the...
Antegrade titanium elastic nailing can be performed with the patient in a supine or lateral decubitus position. Advantages of using a radiolucent flat-top table include ease and speed of setup, ease of imaging, and the ability to perform multiple surgeries simultaneously in a polytrauma patient. We prefer to use hip positioners rather than bean bags for lateral positioning.

The leg is held elevated off the table and prepped in the standard fashion from iliac crest to toes. A 5-cm incision is made over the tip of the greater trochanter in line with the femoral shaft. The fascia and abductor muscles are split longitudinally to expose the proximal trochanter. The trochanter is most prominent in the lateral position, and exposure is easy. Anterior and posterior margins of the trochanter are palpated, and care is taken to protect the posterior vessels. An awl or guide pin is placed in the starting position lateral to the tip of the trochanter. Guide pin position can be confirmed radiographically. Use of a guide pin requires the additional step of using a cannulated drill. A ball-tip guidewire with a subtle bend, placed at the end prior to insertion, is used to facilitate passage at the fracture site and positioning in the distal femur. Following fracture reduction, the guidewire is advanced distally, with care taken not to penetrate the distal femoral physis. When reaming is preferred, it is initiated using the smallest end-cutting reamer and progresses to the desired width (typically 1 to 1.5 mm greater than the nail diameter). The nail is inserted. For trochanteric entry nails with a built-in anterior bow, nail insertion is started with the convexity of the bow medial; then it is externally rotated to anatomic position. Proximal and distal interlock screws are placed in a standard fashion. We prefer to place an end cap proximally for ease of nail removal, if necessary.

Open Fracture

When managing open femoral shaft fractures in children and adolescents, it is important not to underestimate the amount of energy required to create an open fracture. Immediate IM nailing with flexible or rigid nails is appropriate in patients with open fractures in whom the external wound can be closed and adequate débridement performed. IM nailing of extensive open injuries should be carefully considered on an individual basis because these injuries are associated with longer time to union and a higher complication rate.

The decision to perform immediate or delayed nailing depends largely on the status of the soft tissues (ie, whether closure is possible or soft-tissue coverage is required), the status of the wound bed, the presence of concomitant vascular injury and/or bone loss, and the fracture pattern. External fixation should be performed if soft-tissue coverage cannot be achieved and/or the wound is grossly contaminated. Conversion to definitive fixation can be done when wound coverage can be obtained. In the interim, the wound can be managed with an antibiotic bead pouch and/or a vacuum-assisted closure device. Repeat irrigation and débridement should be done every 48 to 72 hours until definitive soft-tissue coverage is achieved.

Postoperative Care

Immobilization and Weight Bearing

No consensus exists in the literature regarding postoperative immobilization and the optimal progression of weight bearing following IM fixation of pediatric femoral shaft fracture. In particular, consensus is lacking re-
garding the use of flexible nails, which act as a load-sharing internal splint. Flynn et al\textsuperscript{17} found that use of a knee immobilizer until a callus is visible radiographically (ie, approximately 4 to 6 weeks postoperatively) helped to limit pain, provided support to legs with weak quadriceps muscles, and led to decreased soft-tissue irritation at the knee. In patients with questionable stability (ie, unstable fracture pattern, questionable fixation quality, uncertain patient compliance), 1 to 2 months in a hip spica cast or a hinged knee-ankle-foot orthosis was found to be a viable supplement to treatment. In a series of 39 patients treated with flexible IM nails, Luhmann et al\textsuperscript{16} used postoperative immobilization in patients with fracture comminution, a narrow canal diameter that precluded adequate fracture stabilization with the nail, and significant soft-tissue stripping. (Increased patient size was not indicated as a reason for postoperative immobilization.) Patients were immobilized with either a one and one-half leg spica cast or a hinged knee-ankle-foot orthosis until a callus was visible radiographically (20 days after fracture). Immobilization is rare following fixation with rigid nails because this construct provides improved canal fill and the strength of a statically locked, rigid implant.\textsuperscript{19}

Immediate postoperative weight bearing and weight-bearing progression must be individualized, regardless which nail type is used for fixation. Once callus formation has begun and radiographic and clinical signs of progressive healing are evident, the patient is allowed to progress to full weight bearing.

**Physical Therapy and Return to Athletic Activity**

Given the lack of evidence regarding postoperative physical therapy following management of pediatric femoral shaft fracture, the AAOS clinical guideline work group was unable to recommend for or against physical therapy to improve function.\textsuperscript{4} We recommend physical therapy for patients who lag behind their similarly treated counterparts in terms of ROM, strength, and normalization of gait.

Children and adolescents are increasingly involved in athletics, and determining when a patient can return to athletic activity is of paramount importance. The clinician may therefore be inclined to prescribe physical therapy to speed the progression of ROM, strength, and proprioception. In our protocol, return to sport occurs approximately 12 to 16 weeks after fixation, following solid bone healing with optimized muscle strength and motion.

**Implant Removal**

Implants that cause soft-tissue irritation or pain, knee effusion, or loss of knee ROM may be removed after callus formation has occurred and the fracture line is no longer visible radiographically.\textsuperscript{1} The AAOS work group could not recommend for or against implant removal in asymptomatic patients following management of diaphyseal femur fracture.\textsuperscript{4}

Other than soft-tissue irritation, few complications have been reported in association with retained implants in the pediatric population. However, premature implant removal can lead to refracture.\textsuperscript{5} Implant removal, particularly removal of rigid nails, is associated with a risk of osteonecrosis in the proximal femur in the setting of extensive dissection.\textsuperscript{11}

**Summary**

IM fixation of femoral shaft fracture in children and adolescents has changed substantially with improved understanding of proximal femoral vascularity. Typically, IM nailing is associated with high union rates and low complication rates. In children aged 5 to 11 years, good results can be obtained with elastic or flexible retrograde nailing. Typically, rigid nailing is reserved for the juvenile patient with a high body mass index (eg, >30) or the adolescent patient (ie, aged ≥11 years).

Selection of a fixation method is based on several factors, including patient age, body habitus, and femoral morphology, as well as fracture characteristics, the presence of associated injuries, and the surgeon’s preferred nailing technique. Other important technical considerations include intraoperative patient positioning, use of traction or a fracture table, and potential IM reaming. Adherence to meticulous surgical technique, particularly nail starting point, reduction, and rotational alignment, is of paramount importance. Carefully planned and well-executed IM fixation, followed by early mobilization, is an effective and well-accepted modality for managing femoral shaft fracture in the pediatric population.

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**References**

*Evidence-based Medicine: Levels of evidence are described in the table of contents. In this article, references 9, 11, 14, 15, 21, 22, 29, 31-33, 35, 39-42, 44, 45, and 47 are level I studies. References 6 and 38 are level II studies. References 1-5, 7, 8, 17-19, 23-25, 27, 34, 36, and 37 are level III studies. References 10, 12,
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13, 20, 26, 28, and 46 are level IV studies. Reference 16 is level V expert opinion.

References printed in bold type are those published within the past 5 years.


