9 Motorized Intramedullary Lengthening, an Emerging Technology for Limb Length and Deformity Correction

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Introduction

The first description of limb lengthening is credited to Codivilla in 1905 [1]. Limb lengthening has evolved from an open step-cut osteotomy, distracted by bed-confined traction, to Ilizarov's methodology of distraction osteogenesis whose principals include a blood preserving corticotomy, a latency period, regular rate and rhythm of distraction, stable circular external fixation, and functional use of the extremity during treatment. Three decades ago, a small cadre of surgeons learned Ilizarov's methods directly from him, and they are now passing this information on to the next generation of limb reconstruction surgeons. With this "passing of the torch," we now have the option of a technical refinement to the process, that is, remotely controlled, motorized, telescopic, intramedullary lengthening nails. The discomfort associated with the prolonged use of external fixation of any kind is often poorly described in the literature, but is well known to patients and surgeons. Although the Ilizarov methodology included many innovative biological and mechanical concepts that were previously unknown, external fixation is not without its problems, which include length of time required for the treatment, pin site infection, soft tissue tethering, and scarring at the pin sites, with patients often expressing dissatisfaction during the process. This chapter describes the latest methods of delivering Ilizarov's principles to patients by fully implanted, motorized, telescopic, intramedullary lengthening nails.

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Indications

The primary indications for bone lengthening and deformity correction with motorized intramedullary lengtheners include limb length discrepancy resulting from congenital and post-traumatic conditions such as fibular hemimelia, congenital short femur, fracture malunion, and premature growth arrest. Suitable candidates must have completed growth at the adjacent physis, have adequate canal diameter and bone length to accept the available nails, and have a canal suitable for intramedullary nailing. These patients include selected children, adolescents, and adults. Distraction osteogenesis (DO) has been successfully used over the last half-century to lengthen bone. An optimal rate and rhythm of distraction is critical to successful DO, for which external fixation has been a reliable tool [2, 3]. The disadvantages of external fixation frames are well known and include pin tract infections, pain, soft-tissue tethering, and joint stiffness [4]. Limb lengthening complications such as joint contracture, stiffness, subluxation, fracture, residual deformity, and chronic pain are well described [5]. Bone lengthening with a fully implantable device is desirable in order to avoid external fixation, mechanical integrity and accurate control of distraction are mandatory. As with any intramedullary rod, lengthening must occur along the anatomic axis of the bone, which will result in a translation deformity, the effect of which is determined by the original anatomy and the magnitude of the lengthening [6]. The prediction and prevention of these iatrogenic deformities using a novel preoperative planning technique known as "reverse planning" is essential in preventing abnormal mechanical loads in the future [7]. Remote-controlled, motorized, internal lengthening devices (MILD) have recently become available for use in the femur and tibia [8–10].

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History

Ilizarov's remarkable discovery of bone regeneration, commonly referred to as the Ilizarov method, has opened windows into the treatment of many conditions previously considered as hopeless maladies.

It is now possible to combine Ilizarov's principles with those of intramedullary fixation for limb lengthening by using preoperative planning, less invasive surgery, temporary intraoperative external fixation, specific reaming techniques, and intramedullary fixation. Telescopic nails with miniature motors are remotely controlled by either radio frequency or magnetic energy [8, 11]. These techniques require precise planning and execution because only axial length can be adjusted after the surgery without an additional operation.

Distraction osteogenesis (DO), largely introduced by Ilizarov, now enables us to lengthen bones in children with conditions such as fibular hemimelia or a congenitally short femur without the additional need for bone grafting [2, 3]. We spare these children additional surgeries by tapping the body's capacity to form regenerate bone, but the new bone requires the prolonged use of external fixators throughout consolidation. Fractures, stiffness, and residual deformity are often a result of months in external fixation. With DO, we are also able to achieve union in congenital pseudarthrosis of the tibia more predictably, a formerly hopeless condition which often resulted in amputation after multiple attempts at union with bone graft, pins, and casting [12]. The correction of severely deformed limbs from developmental, infectious, and traumatic conditions such as Blount's disease by using simultaneous, gradual angular, rotational, and length corrections can now be more precisely performed with web-based computer analysis than with the Ilizarov device with six-axis correction [13]. Massive bone defects resulting from trauma, infection, and tumor can be filled by spontaneously regenerating the patient's own bone by compressing the defect site while growing new bone at a remote site [14].

Despite these extraordinary gains in the field of limb lengthening and deformity reconstruction, patients and their families must endure months of pin site maintenance and the ever-present external fixation. The resulting soft tissue scarring can lead to further contracture and difficulty with mobilizing the adjacent joint(s). Additionally, it takes years and scores of cases for surgeons to learn and then become experts in Ilizarov's methods. Even after years of experience with bone regeneration, surgeons commonly confront yet another new complication arising from the treatment [5].

Intramedullary fixation to supplement external fixation during limb lengthening has lead to a new generation of limb lengthening technology, described in a separate chapter as "hybrid lengthening". These techniques include lengthening over nail and plate assisted lengthening, each of which reduces the time spent in external fixation [15–17].

The "Holy Grail" of limb lengthening could be considered an intramedullary nail capable of bone fragment stabilization, gradual deformity correction, and lengthening, obviating the need for external fixation altogether. Such a device is not currently available since intramedullary nails are only capable of bone stabilization and gradual lengthening or shortening. The correction of angulation, translation, and rotation must be done acutely by the surgeon at the initial surgery, limiting its applicability due to potential neurovascular compromise and damage to potential bone regeneration.

A Brief History of Internal Limb Lengtheners

Bliskunov described an internal lengthening device that consisted of an intramedullary femoral rod bolted to the iliac wing and lengthened by a ratchet mechanism [18]. Cole introduced a device, the intramedullary skeletal kinetic distractor (ISKD), that is actuated by the inherent rotational characteristics of gait [19]. The Albizzia nail, introduced in France by Guichet, also has mechanical actuation [20]. The Albizzia and ISKD are still in use, but require the patient to perform intermittent axial rotation of the limb to effect distraction. These modalities perform well, albeit rate control difficulty is reported with each [21, 22] (Figs. 9.1 and 9.2).

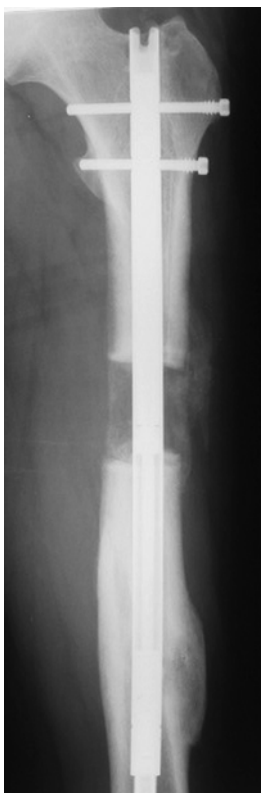

Fig. 9.1 The ISKD was found to be most useful for posttraumatic femoral length discrepancies

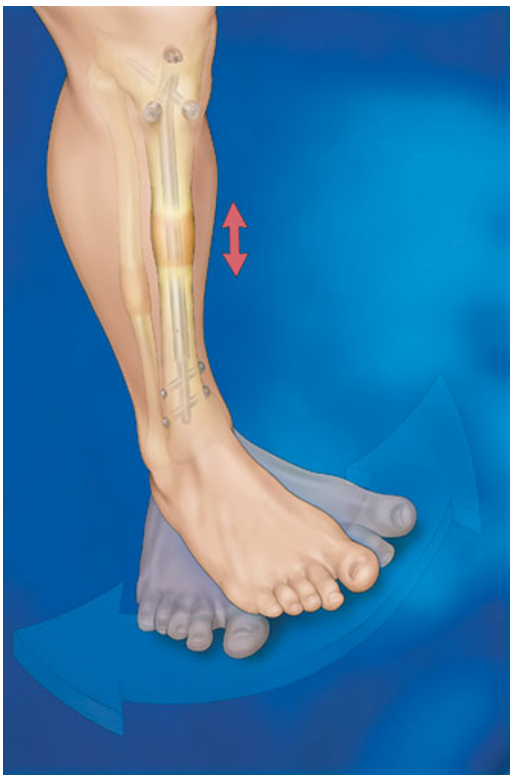

Fig. 9.2 The ISKD and Albizzia nails are activated by manual limb rotation

Fig. 9.3 The FITONE nail has an attached cable and antenna. The transformer box shown converts electric current to radiofrequency waves, transmitting energy transcutaneously

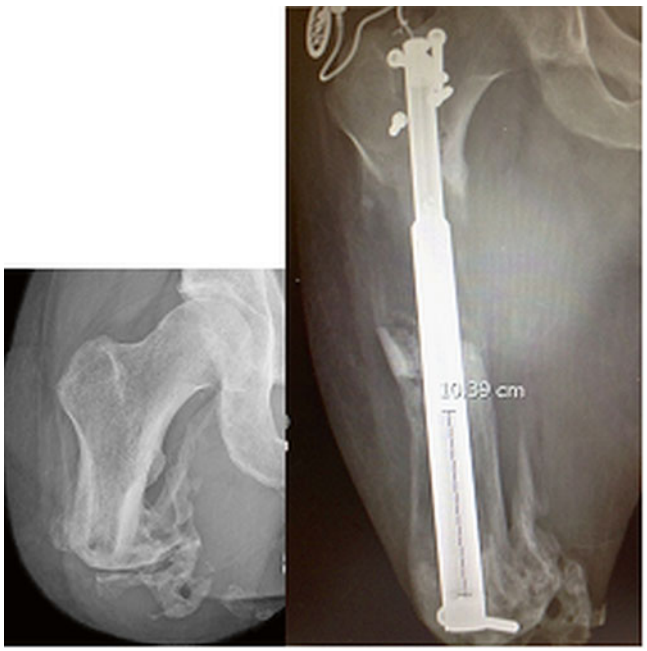

Fig. 9.4 (**a**, **b**) The FITBONE stump lengthener was used to lengthen a traumatic above knee amputation for a total of 18 cm, allowing the patient to be fitted with prosthesis and walk without assistive devices

A new era has begun with the introduction of intramedullary lengthening devices whose distraction is controlled by an external power source which causes an internal actuator to effect the desired amount of distraction. Baumgart and Betz first introduced such a device in 1992 [8]. Baumgart further developed specific insertion tools for the FITBONE nail (Wittenstein Intens, Igersheim, Germany), and published a novel planning method in 2009 [7]. The FITBONE device employs an electric motor imbedded in the telescopic rod, which is activated by intermittent transcutaneous transmission of radiofrequency waves to a subcutaneous receiver that converts these waves into an electrical impulse discharged via a connecting cable (Fig. 9.3). Distraction only occurs when the transducer is placed directly over the receiver, allowing precise control of distraction rate and rhythm. This device has since undergone multiple improvements, and the current generation has been used in over 2,000 cases worldwide. Models suitable for antegrade, trochanteric, and retrograde femoral use are available. A tibial model is in use as well. A bone transport device and a model for short amputation stump lengthening are also available (Fig. 9.4a, b). The FITBONE device requires specific training under the direction of its inventor, Professor Rainer Baumgart or a designee. The FITBONE device is currently available in the USA only under an FDA-approved compassionate use exemption.

The PRECICE nail (Ellipse Technologies, Irvine, CA) was FDA-approved and introduced in 2012. The telescopic nail has a magnetic drive mechanism that is activated by a handheld external electromagnetic controller. Similar to FITBONE, the surgeon instructs the patient in its use, and the device is specifically programmed by the surgeon to prevent application of an improper rate. The patient or family member then performs the distraction by applying the controller directly over the internal magnet in the limb three

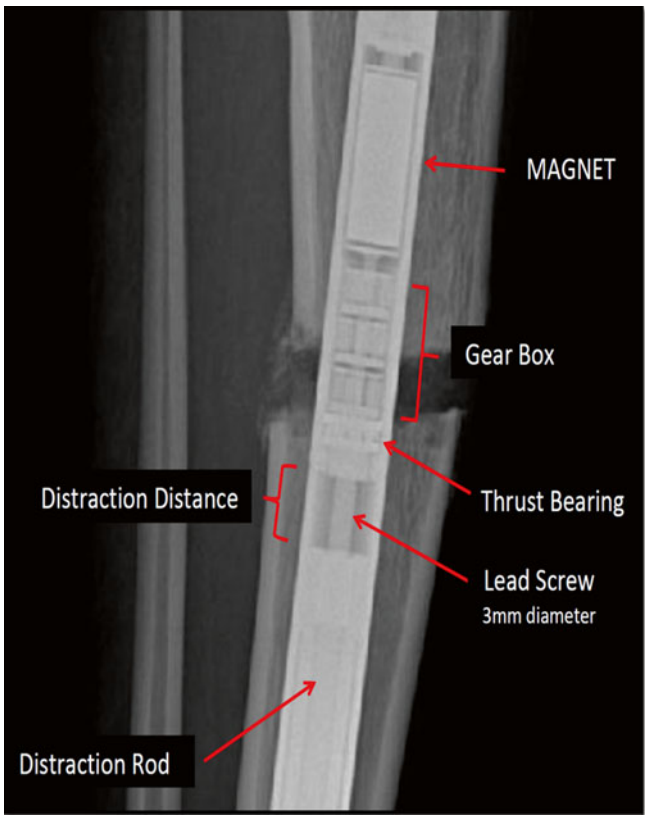

Fig. 9.5 The PRECICE mechanism has a spindled magnet attached to gear boxes which rotate against the distraction rod

to four times daily, with the rate and rhythm being adjusted according to weekly clinic visits and radiographs. This device can apply either compression or distraction, does not require a cable/antenna-receiver, and is fully FDA-approved. The manufacturer recommends specific advanced instruction for its users. Either device requires removal after complete corticalization has developed, typically 1–2 years after placement. The PRECICE device has now been used in over 800 cases worldwide (Bart Balkman, Ellipse Technologies, personal communication) (Fig. 9.5).

General Guidelines for Motorized Intramedullary Limb Lengthening

As with all limb lengthening procedures, appropriate surgeon education is essential. The properly educated surgeon then organizes a dedicated team of nurses, therapists, and orthotists to ensure the comprehensive care of these patients who often have complex medical and psychosocial issues.

Preoperative studies include a standing film of both lower extremities with block leveling of the pelvis. Foot height differences are considered to be part of the tibial discrepancy. A standing lateral film of the femur or tibia is necessary, inspecting for obvious angulation as well as the more subtle variation in the canal thickness often observed in longstanding deformities. All X-rays are made with a magnification marker so that the segment length and canal diameter can be accurately measured.

The Reverse Planning Method

The Reverse Planning Method described by Baumgart begins with defining the final ideal correction accounting for length, angulation, and translation [7]. This method can be used with any approach to the femur or tibia, but is particularly necessary for femoral lengthening, as intramedullary lengthening along the anatomic axis of the femur will cause medial translation of the knee and lateralization of the mechanical load to the knee. This coronal plane translation has been estimated at 1 mm per centimeter of lengthening, but depends on the magnitude of the preoperative deformity, the location of the corticotomy, the neck-shaft angle, and the length to be achieved [23]. Deformity correction with an intramedullary nail must then occur acutely intraoperatively, anticipating the future position of the knee. Intramedullary lengthening of the tibia does not typically lead to similar translation problems since the tibial anatomic axis normally approximates its mechanical axis.

It is important to execute the following steps with precision in the preoperative planning process (Fig. 9.6a–g).

Step 0

Make a full-size tracing of the radiograph of the entire lower limb, marking reference points, angles, and lines. Once the bone to be corrected and lengthened is determined by the malalignment test [24], consider its curvature in both the coronal and sagittal planes. If a straight track for the nail cannot be achieved, an alternate corticotomy site or a second osteotomy should be considered. If the medial proximal tibial angle (MPTA) is normal (85–90°), continue the tibial mechanical axis line to a point well above the current femoral head location (see Fig. 9.6a).

Step 1

Draw and extend the mechanical axis of the tibia proximally with sufficient length to account for the lengthening goal (see Fig. 9.6b).

Step 2

Draw the location of the femoral head in its final position after lengthening along the mechanical axis has occurred (see

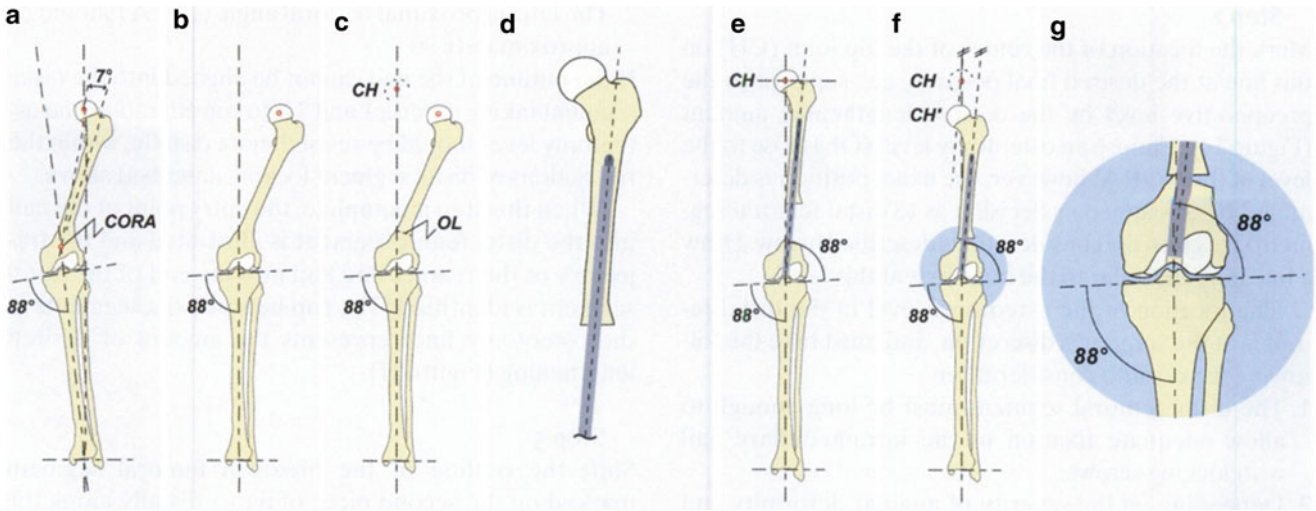

Fig. 9.6 (**a**–**g**) Reverse Planning Method for retrograde nailing of the femur

Fig. 9.6c). Choose a corticotomy level near the deformity apex, but of sufficient distance from the knee joint to allow for both locking and blocking screw insertion (generally 7–10 cm from the knee joint line). Depending on the severity of the deformity and the magnitude of the planned lengthening, selection of a corticotomy site too distant from the knee may result in excess cortical reaming and undesirable conditions for healing.

Step 3

A second tracing is made outlining the proximal femur to the level of the corticotomy (see Fig. 9.6d). The anatomic axis is then defined and drawn, and the nail is outlined to scale. In this step, the surgeon must consider the effect of reaming in both planes, being certain that cortical integrity is maintained to accommodate the size of implant and characteristics of the bone.

Step 4

After overlapping the second tracing on the first, and placing the femoral head in its future location, the papers are then swiveled until the anatomic axis lines are matched. The nail tracing should enter the distal fragment in a position of anatomic harmony, and the mechanical lateral distal femoral angle (LDFAm) should approximate 90° (see Fig. 9.6e).

Step 5

Shift the outline of the second drawing distally along the anatomic axis line to the point where contact is made between the corticotomy ends (see Fig. 9.6f). This image of the bone segment and nail position, including angulation and translation, now becomes the intraoperative goal (see Fig. 9.6g). It will replicate the desired intraoperative position with regard to sagittal translation and angulation, and should allow the exact nail position to be duplicated. If coronal deformity exists, the corticomy can be manipulated directly with an osteotome and/or indirectly with Shanz pins and sterile bumps.

Visual Aids

Creating visual aids for surgery can be helpful in many ways. The preoperative plan, printed full size, is secured to the surgical suite wall, next to the patient radiographs. Skin markings are then created. The fluoroscope is brought into the field in the AP projection. The hip, knee, and ankle reference points and lines are marked on the overlying skin with a sterile marking pen. The anatomic and mechanical axes are marked on the bone to be treated. The patella and infrapatellar ligament are marked since they are used to maintain consistent AP positioning. The proposed corticotomy site is marked (Fig. 9.7).

The selected nail is opened and the proximal, distal, and telescopic portions are indicated with skin clips to identify the desired reaming depth. Anatomic hazards to be avoided, such as growth plates, are also marked. These marks are then used for visually referencing Shanz pin insertion and reaming paths, and for assisting the surgeon in reducing X-ray exposure (Fig. 9.8).

Venting the Canal

Reaming a closed long bone causes elevation of intramedullary pressure and intravasation of marrow contents, with the potential for creation of fat embolism. This complication is

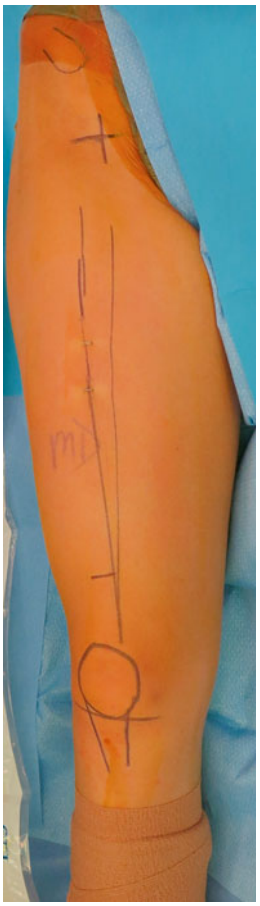

Fig. 9.7 Sterile markings are made on the surface of the skin to aid canal preparation

best avoided by venting the canal to decrease the marrow pressure [25]. The planned corticotomy site is routinely selected as the venting site. This site is drilled (vented) in percutaneous or open fashion using a subperiosteal approach prior to instrumenting the canal. A series of 4–5 mm drill holes allow intramedullary reamings to spill at the corticotomy site, also adding biological support to the lengthening site (Fig. 9.9a, b).

The actual corticotomy will be performed at a later point in time after the canal preparation.

Shanz Pins

Shanz pins are inserted with c-arm guidance in the lateral position. The femoral condyles are rotated so as to overlap each other on a lateral view, and the pin is inserted from lateral to medial, just inside the posterior cortex at the junction of the metaphysis and epiphysis, and out of the way of the future passage of the nail (Fig. 9.10).

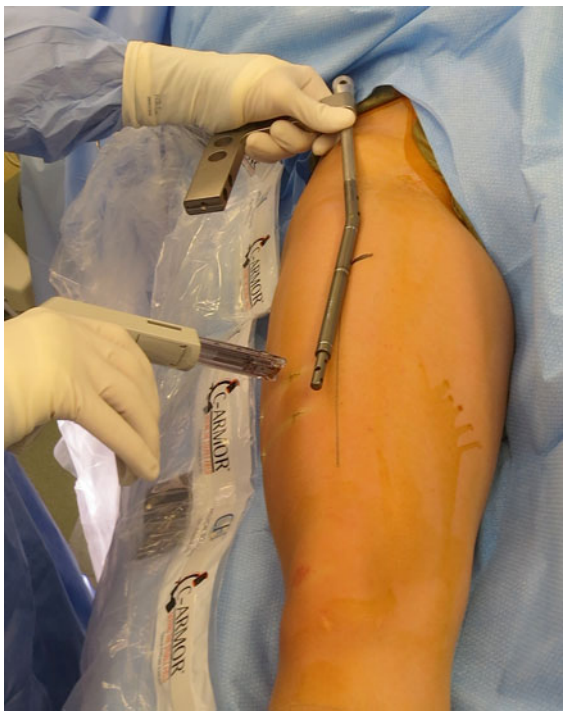

Fig. 9.8 Reaming depth can be guided by applying skin clips at the appropriate levels

Entry Points

Ideal entry points are required for proper intramedullary nailing and are defined by several authors [26, 27] (Fig. 9.11a, b).

The correct starting point for trochanteric entry is actually on the further-most point medial on the tip of the trochanter without entering the piriformis fossa.

Reaming Techniques

As the telescopic nails are straight and the canal is not, one must either over-ream a curved canal to accommodate the straight nail, or 'fit' rigid reaming to match the straight nail. After the canal has been vented and the Shanz pins placed, reaming can proceed with attention to appropriate entry points suitable to the approach chosen [26, 27].

Conventional Reaming

The canal is first vented. A bulb tipped guide wire is placed. Flexible reamers prepare a cylindrical path but curve at multiple apices, thus requiring over-reaming of 2 mm to accommodate a straight nail. Corticotomy is generally performed after this "over-reaming" with flexible reamers.

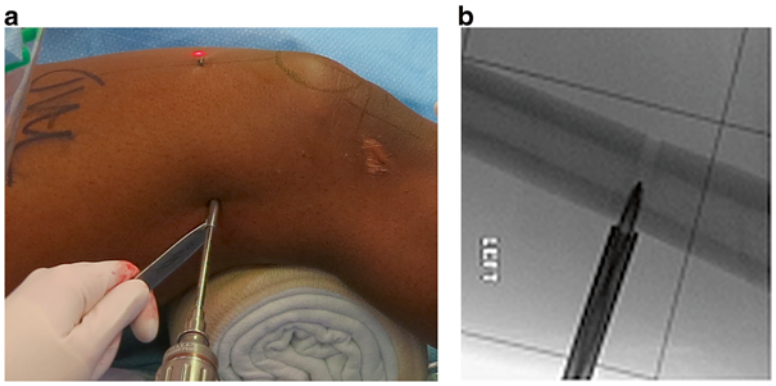

Fig. 9.9 (**a**) Venting the canal at the level of the future corticotomy is done with a series of drill holes, thus creating a subperiosteal pocket into which reamings will spill. (**b**) A 5-mm drill bit with sleeve serves this purpose

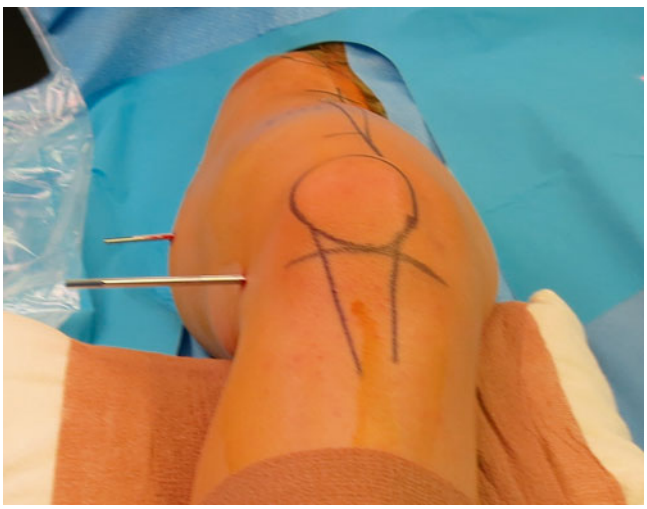

Fig. 9.10 The knee joint skin mark assists parallel Shanz pin insertion without switching c-arm position. The proximal pin is placed rotationally parallel to the distal pin, at the level of the lesser trochanter, perpendicular to the shaft, and posterior to the future nail path

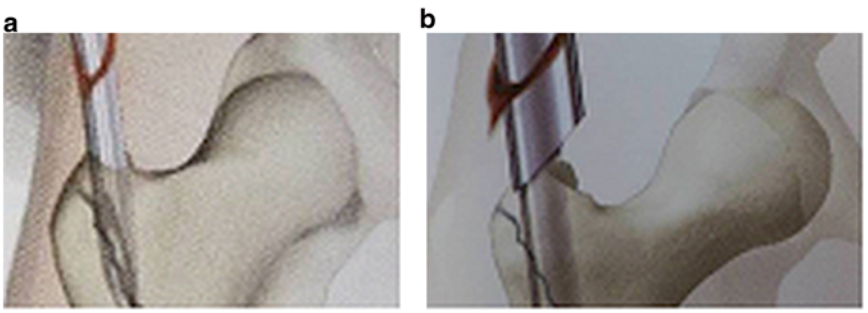

Fig. 9.11 (**a**) Trochanteric entry is at the medial-most tip of the trochanter. (**b**) Reaming sleeves protect soft tissue

Rigid Reaming

The canal is first vented. Canal preparation with rigid reamers creates a well-defined pathway for the straight nail with a future line-to-line fit. Blunt or sharp rigid reamers can shape curved canals with asymmetric wall thickness to accept the nail (Fig. 9.12a, b).

Reaming sleeves passed over insertion dilators protect soft tissues from the reamer blades and prevent spillage of marrow contents into the joint or soft tissues.

Rigid reamers are inserted within the tubes along the planned pathway, and are increased in 0.5 mm increments to 0.5 mm greater than the nail diameter. After canal preparation on the "near side" of the corticotomy, the corticotomy is completed with an osteotome and the deformity is corrected to match the plan in step 5. With the plan achieved, reaming then proceeds on the "far side" of the corticotomy to the 0.5 mm greater than the nail diameter.

Regardless of reaming technique, the nail is inserted with simple hand pressure, reaming slightly more as necessary to

avoid mallet use, and potential damage to the micromotor. Alignment is checked, the corticotomy is compressed, and locking screws are inserted.

Blocking Screws

Blocking screws (Poller) are known to be useful in trauma and reconstruction applications of intramedullary fixation for correcting and preventing deformity [28, 29]. They function to narrow a canal in epiphyseal and metaphyseal areas, and thus guide nails in juxtaarticular applications (Fig. 9.13 a–c).

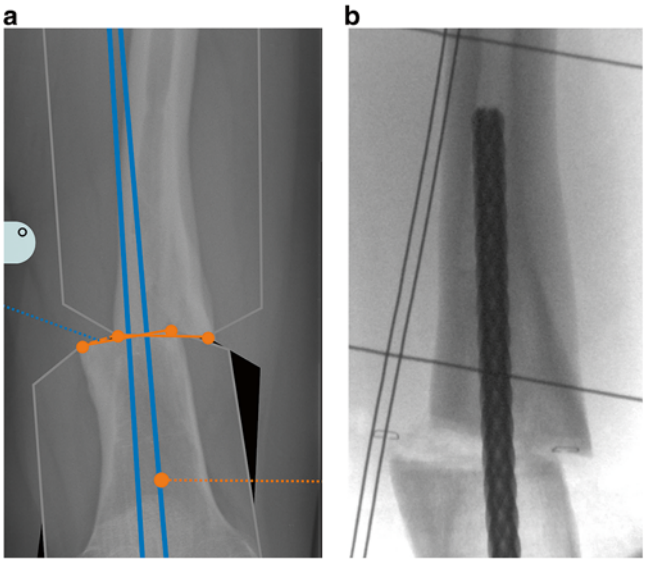

Fig. 9.12 (**a**) Carefully inspecting the canal preoperatively determines if the canal will accept an intramedullary nail. (**b**) In specific instances rigid reamers may be used to "shape" the inner canal

We have learned from our bone lengthening experiences that deformities developing during lengthening are a common event. Asymmetric muscle forces imposed by unequal muscle mass, muscle anatomy, and two-joint muscles create the predictable deformities of varus-procurvatum during femoral lengthening and valgus-procurvatum during tibial lengthening. The development of such deformities can be corrected by adjustments of the fixator in the outpatient clinic when lengthening with circular external fixation. When lengthening with intramedullary techniques, these deformities must be anticipated and prevented with the appropriate use of blocking screws, as later correction requires additional surgery.

Antegrade Femoral Lengthening

Patient Indications

Antegrade femoral lengthening is indicated for patients with leg length discrepancy originating from the femur. Angular and rotational deformity of the proximal to mid femur can be corrected acutely, with the latency period suitably delayed to account for the correction magnitude. A piriformis entry can be used for adults. A trochanteric entry has been shown to be safe for preadolescents as young as age 12 years [30] (Fig. 9.14a, b).

Lengthening along the anatomic femoral axis will result in 1 mm of knee medialization for every 10 mm lengthened, potentially resulting in an undesirable transfer of load laterally [18]. Assessment of the weight-bearing line on preoperative full-length AP X-rays will be helpful in determining whether this amount of medial translation will be harmful to the knee in the future. Acute deformity correction can be assisted by temporary intraoperative placement of Shanz

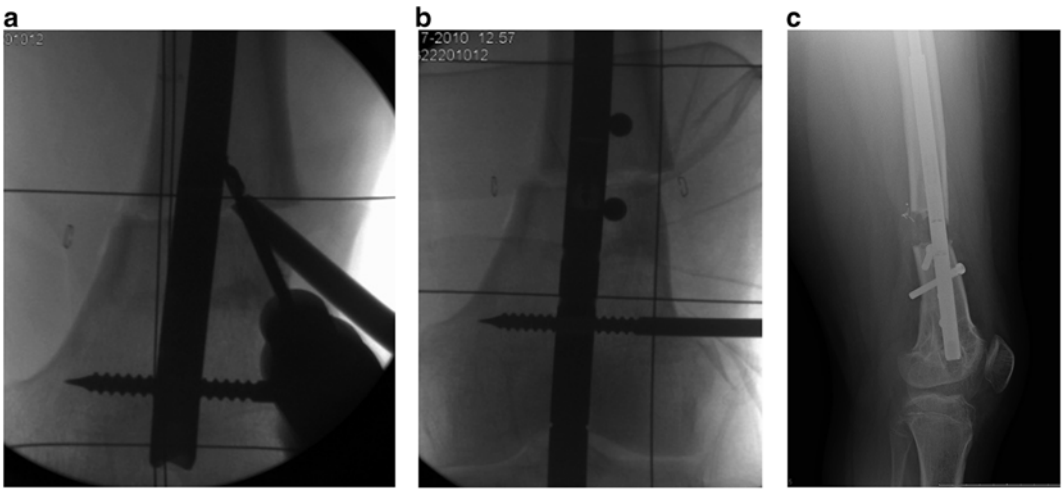

Fig. 9.13 (**a**) Blocking screws are placed against the nail. (**b**) Blocking screw location is specific to each case, generally on the "concave" side of potential deformity. (**c**) A single posterior screw maintained this extension osteotomy

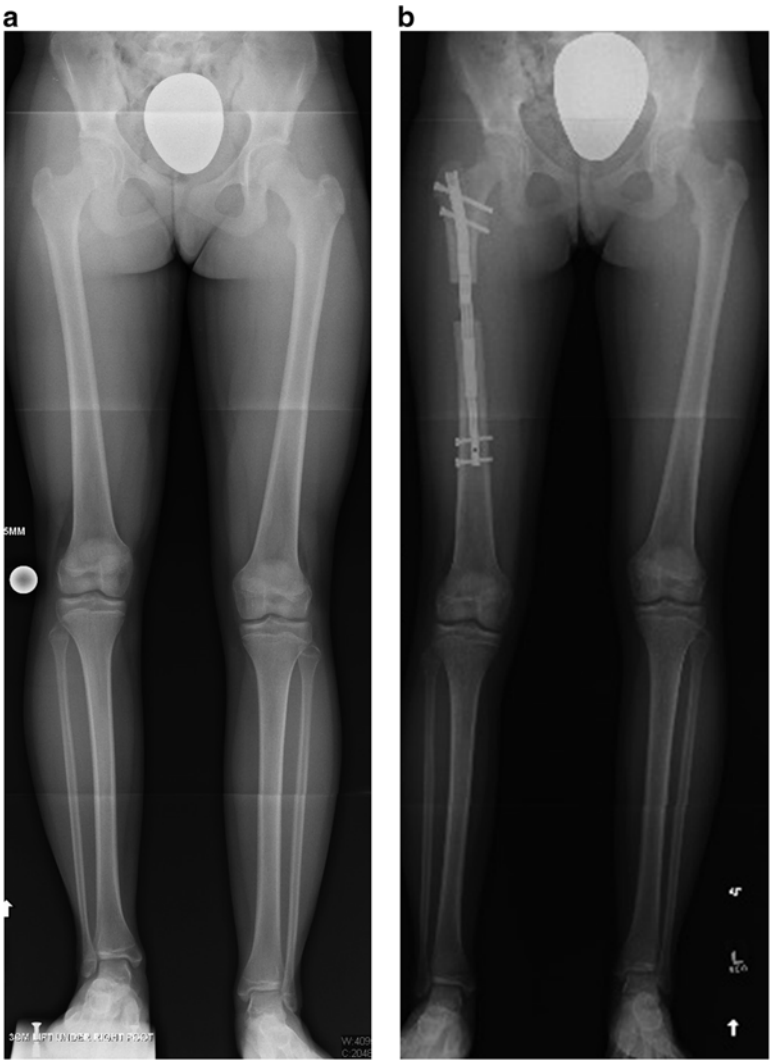

Fig. 9.14 (**a**) A 16-year-old girl with a 3.5-cm idiopathic right femoral shortening with preoperative weight bearing line 2 mm medial to the medial spine, suggests an antegrade lengthening will result in lateralization of 3.5 mm. (**b**) A trochanteric entry best avoids the hip vasculature, and resulted in the predicted and acceptable weight bearing line 1 mm lateral

pins, and progressive deformity during lengthening can be prevented by blocking screws (Fig. 9.15a–c).

Planning for Antegrade Femoral Lengthening

A graphical method of planning has been described for length and deformity correction [31]. The corticotomy should be made at the apex of the deformity in the coronal and sagittal planes, when possible.

Antegrade Femoral Technique

A radiolucent table and a bump under the ipsilateral buttock are used. Sterile draping must provide adequate exposure of the proximal buttock for nail entry. The ipsilateral arm is supported across the chest and protected during reaming. At the planned corticotomy level, a 1-cm incision is made and multiple holes are drilled in a transverse fashion, venting the canal. Shanz pins are placed in the proximal and distal segments away from the nail tract to mark rotation and control the bone segments.

Careful preoperative evaluation of individual hip anatomy allows determination of the ideal piriformis or trochanteric entry. For example, a proximal femoral flexion deformity requires a more posterior entry point. Acquired hip deformities such as anterior displacement of the greater trochanter can malign the entry point as well. The hip is adducted and a wire is inserted into the intramedullary canal through the piriformis fossa or medial tip of the greater trochanter. A 2-cm incision is made over the wire, and a soft-tissue protector is inserted. The intramedullary canal is opened with a cannulated drill, and then reaming is performed by either of the previously described methods. The assembled nail is inserted upto the corticotomy site. An osteotome is used to finish the corticotomy, with completeness confirmed by fluoroscopy. Deformity correction is completed directly by osteotome

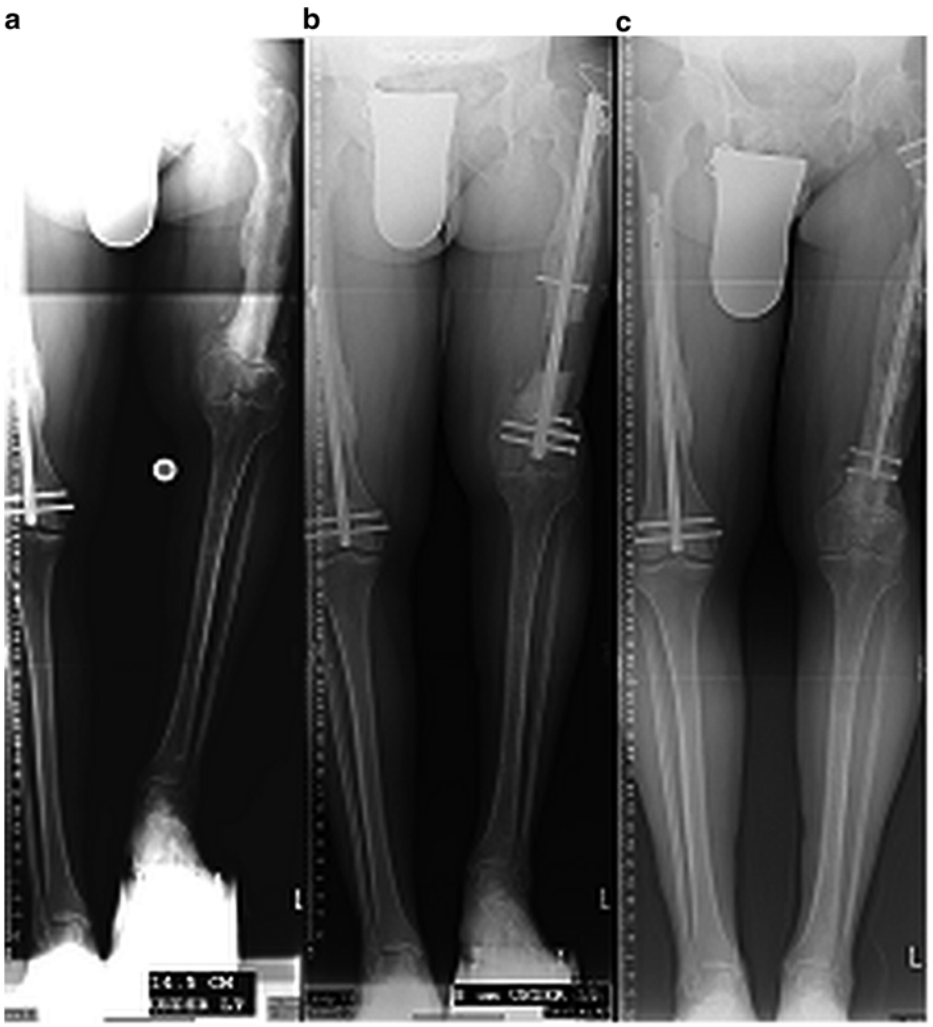

Fig. 9.15 (**a**) Post traumatic knee ankylosis makes an antegrade approach to this femoral lengthening necessary. (**b**) Childhood Perthes altered proximal femoral anatomy; making piriformis entry more suitable for the first femoral lengthening of 8 cm. (**c**) The second lengthening was similarly approached through the piriformis fossa

Box 9.1. General Guidelines Summary

1. Blocking screws should be employed to prevent deformity at insertion or during lengthening. They are less likely needed if the deformity and corticotomy apex is at the isthmus, and/or the lengthening is small, less than 3 cm.
2. Blocking screws are most commonly needed in the distal femur and proximal tibia, as these locations often have large canal-to-nail size ratios.
3. Postoperative monitoring is done weekly during distraction and monthly during consolidation.
4. Preoperatively plan each case with life-size drawings or computer graphic simulation. The Reverse Planning Method is most useful in retrograde femoral applications.
5. Nail length is planned to allow 6–7 cm of the wider portion of the nail in the distracted segment at the completion of distraction.
6. The canal must be vented before reaming.
7. Isthmic bone diameter must be able to accommodate reaming 2 mm greater than the nail diameter for flexible reaming, and 0.5 mm for rigid reaming.
8. Shanz pins control segments and prevent rotational deformity, particularly in femoral lengthenings where the corticotomy is not well visualized through the wound.
9. Periosteum-sparring, non-heat-generating corticotomy should be positioned at or near apex of the deformity.
10. Comminution of the osteotomy should be avoided, as this creates nail instability, may prevent acute correction, encourages lengthening deformity, and may lead to poor bone regenerate.
11. The nail should be advanced by hand pressure only in order to avoid damage of the distraction motor and gear boxes.

manipulation of the osteotomy site or indirectly by bumps and a surgical assistant. The corrected position of the osteotomy may be secured with a femoral distractor or sterile bumps. The nail is passed across the osteotomy site correcting any residual deformity. Rotation is optimally set by rotating the Shanz pins into their pre-osteotomy position, and the proximal interlocking screws are inserted via the targeting jig. The corticotomy is manually compressed. Proper alignment is checked and adjusted using an alignment grid, long alignment rod, or Bovie cord. Distal locking screws are inserted using the "perfect-circle" freehand technique. Iliotibial band release is performed for lengthening of greater than 3 cm and in cases of congenital origin.

Retrograde Femoral Lengthening

Patient Indications

Retrograde femoral lengthening is indicated for skeletally mature patients with the any of the following:

1. Where antegrade femoral lengthening will result in excessive axis deviation or translation
2. Hip arthrodesis or deformity of the proximal femur preventing antegrade femoral nailing
3. Distal femoral deformity suitable for acute correction and retrograde nailing (Fig. 9.16a, b).

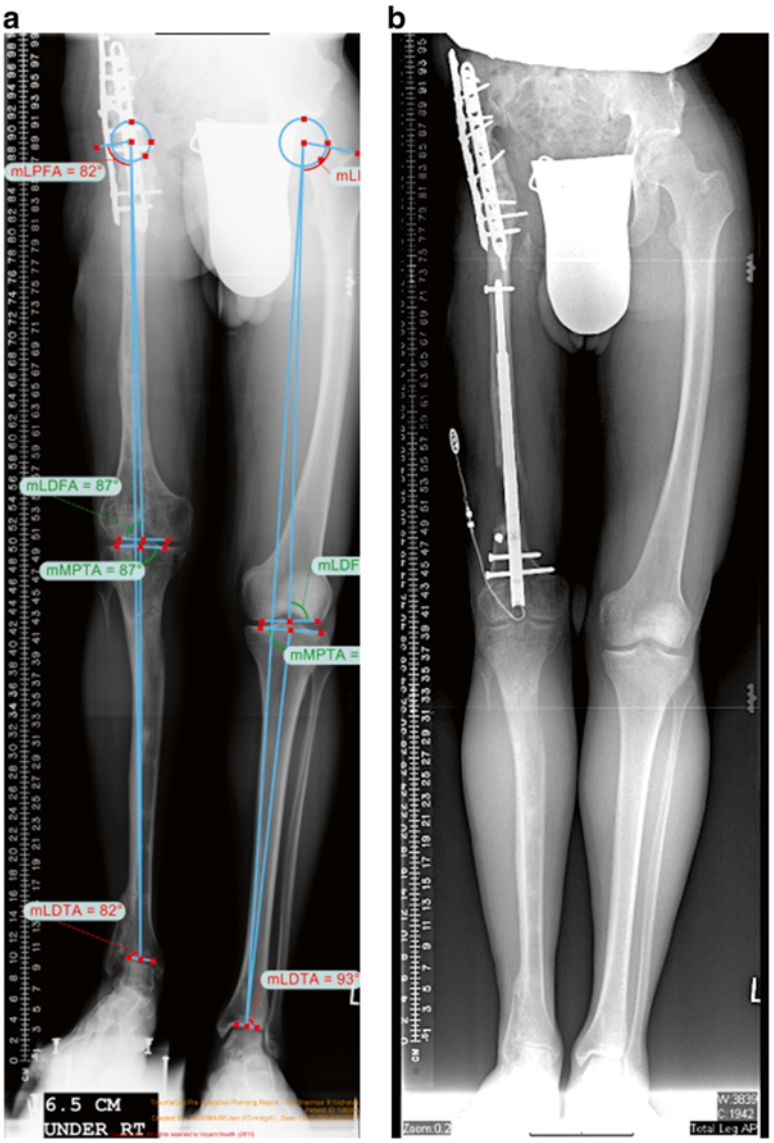

Fig. 9.16 (**a**) Hip arthrodesis was performed after proximal femoral osteosarcoma resection. (**b**) A retrograde femoral lengthening was the necessary approach for the 6.5-cm limb length discrepancy

A retrograde femoral approach is also indicated in skeletally immature patients with premature arrest of the distal femoral physis, provided canal size and bone length is sufficient for straight nail insertion. This technique requires entry through and protection of the knee joint as described by Watson and others [26, 27].

Planning

Retrograde femoral lengthening is routinely planned with the Reverse Planning Method as described by Baumgart [7]. This method of planning can be performed with X-ray tracings of the preoperative full-length standing radiographs, or with commercially available software systems. In either case, it is recommended that the surgeon reproduce the actual size of the entire limb using preoperative, intraoperative, and completed correction X-rays for intraoperative use.

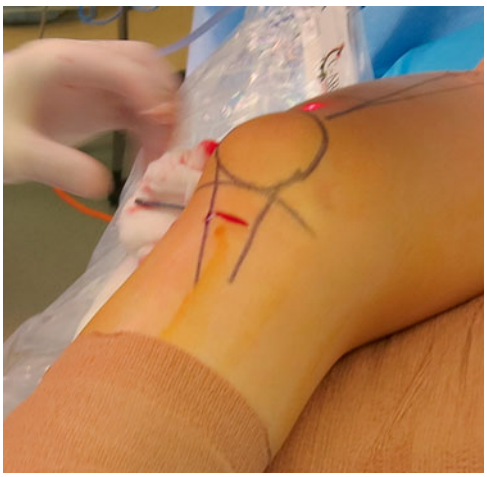

Fig. 9.17 The skin incision for retrograde femoral lengthening is transverse or longitudinal, with a longitudinal incision through the ligament

Retrograde Femoral Surgical Technique

A radiographic grid is placed under the patient, and the hip position is centered over the grid marker. The orientation of the distal joint line, patella, and the anatomic and mechanical femoral axes are marked with sterile skin markers. The corticotomy level, future nail position, and junction of the telescopic portion of the nail are marked with skin clips to guide reaming depth and direction.

The femoral canal is vented through the future corticotomy site by drilling multiple holes through a 10-mm lateral incision. Two Shanz pins are placed, one distal and another proximal to the corticotomy site, in a lateral to medial direction and rotationally parallel.

The infrapatellar ligament is split longitudinally through a 10 mm infrapatellar incision, and a 3 mm guide wire is inserted to a point in the intercondylar notch anterior to the PCL origin, and directed along the path that will allow for reaming of the distal bone segment as planned (Figs. 9.17 and 9.18a–d).

Biplane fluoroscopy guidance for determining the exact entry point avoids hyaline cartilage injury. The articular surfaces are protected from reamers and reamings with a protective sleeve so that insertion, removal and exchange of reamers never touch the articular surfaces, and never actually enter the joint.

Reaming just to the corticotomy level in 0.5-mm increments is performed. The corticotomy is then completed with an osteotome at the venting site. Drilling six to eight 5-mm holes should be adequate to avoid bone spikes at the corticotomy since they may prevent acute deformity correction. The osteotomy site is then angulated, translated, and/or rotated to the preoperatively planned position and held there by a femoral distractor or an assistant. Reaming of the diaphysis is performed to 0.5 mm greater than the diameter of the nail. The nail is inserted with hand pressure, and alignment is checked with the grid. Additional reaming is performed if

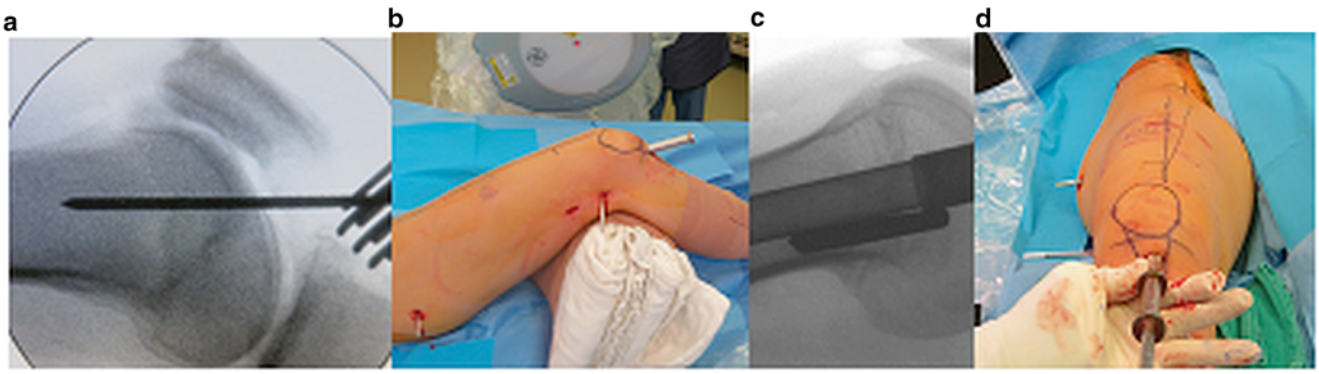

Fig. 9.18 (**a**) A 3-mm guide wire is inserted to the center of the notch, just anterior to the PCL origin and posterior to the articular surface. (**b–d**) Reaming sleeves are inserted, protecting the joint and ligament from reamings and reamer damage

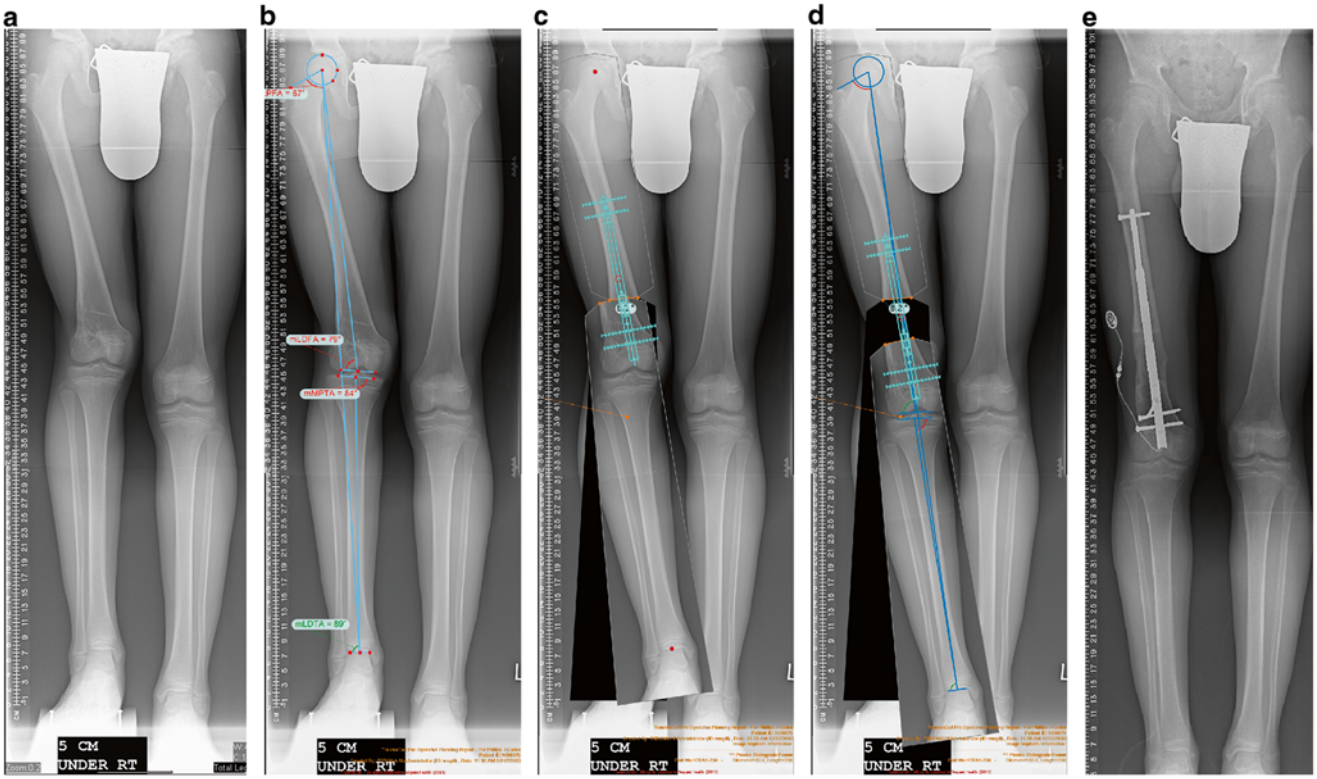

Fig. 9.19 (**a**) Distal femoral physeal closure after fracture resulted in valgus and shortening. (**b**) Properative computer-assisted planning defines, weight bearing line lateral 12 mm, valgus mechanical distal lateral femoral angle 79°, and axial discrepancy of 5 cm. (**c**) Retrograde nail size, position, and translational correction determined by Baumgart's Reverse Planning Method. (**d**) Mechanical axis and weight bearing line and length predicted to be restored to normal after length achieved. (**e**) Full length radiograph demonstrates ideal correction and achievement of goals

the nail does not pass easily. Adjustments in alignment are made if needed and locking and blocking screws are added.

This 14-year-old boy had premature asymmetric distal femoral physeal arrest of the right side, resulting in 9° of valgus and 5 cm of shortening. Preoperative full-length standing X-ray with a lift under the short limb (b) computer-assisted planning (c) corticotomy with intraoperative correction (d) end of lengthening with neutral mechanical axis (e) end result with ideal alignment and matching length (Fig. 9.19a–e).

Tibial Lengthening

Patient Indications

Candidates for tibial lengthening with a telescopic nail are skeletally mature patients with a tibial length discrepancy of 2–6 cm, modest deformity thought to be safely correctable acutely, and an open medullary canal with adequate diameter and length to accommodate the nail.

Planning

Tibial anatomic and mechanical axes are collinear in the undeformed tibia so that planning for translation is unnecessary. A modest tibial deformity can be acutely corrected to allow passage of a telescopic nail, provided that the apex of the deformity (level of the correction) is amenable to stable fixation, and the surrounding neurovascular structures can safely tolerate the acute correction. For example, proximal tibial valgus deformities are at greater risk for peroneal nerve palsy than are proximal tibial varus deformities. Blocking screws are inserted during canal preparation for corrections in the proximal third of the tibia since valgus and procurvatum may develop during lengthening. Corrections in the lower half of the tibia where the bone is wide may not have adequate distal purchase at the end of lengthening, and may also require enhanced fixation with blocking screws. These features limit acute corrections to the region of the junction of the proximal and middle thirds of the tibia, and sometimes to the diaphysis.

Tibial Surgical Technique

Position the patient supine on a radiolucent table with the image intensifier on the opposite side. Sterilely prepare the entire limb, including the foot, leg, thigh, and hip. Perform a fibular osteotomy at the junction of the middle and distal thirds through the internervous plane between peroneal and soleus muscles. Insert a 4.5-mm fully threaded cortical screw distally from the fibula to the tibia with the foot in dorsiflexion. Proximal fibular attachment to the tibia can be accomplished in selected cases using the Rancho technique [32].

A prophylactic anterior compartment fasciotomy is performed in patients at risk for developing a compartment syndrome, such as those with substantial deformity corrections, previous neurovascular compromise, or those anticipating greater lengthening goals (greater than 3 cm). Perform a gastrocsoleus recession if there is existing equinus contracture, or for lengthenings more than a few centimeters or with congenital etiology. Further protection against equinus can be achieved by static or dynamic dorsiflexion bracing or extraarticular pinning as described by Herzenberg [33].

Use an infrapatellar incision, and longitudinally split the tendon or approach the tibia medial to the tendon. Obtain a starting point in the center of the intraarticular area under biplanar image intensifier control.

Choose the tibial corticotomy level at the deformity apex, at least 8 cm from the proximal joint line, thereby allowing room for both locking and blocking screws. Plan the nail length such that there will be 6–7 cm of the wider portion of the nail in the distal segment after distraction is complete [33]. The corticotomy is performed through a 2–3 cm vertical incision, with a tiny elevator lifting the medial and lateral periosteum. Multiple 5 mm drill holes will vent the canal.

Shanz pins are placed rotationally parallel to each other, yet parallel to the adjacent joints in the coronal plane. The tourniquet, if used, must be deflated before entering the canal and reaming. Ream in 0.5-mm increments with either rigid or flexible reamers, and do so with soft tissue protection and a flexed knee supported on a padded triangle. Posterior and medial blocking screws are placed at this time, guiding the reamers along a path to prevent a valgus and procurvatum deformity.

The corticotomy is completed with an osteotome, the knee is flexed, and the nail inserted by hand pressure. The proximal interlock jig will require removal to confirm alignment, as the knee will not fully straighten with the jig in place. When satisfied with alignment, insert the proximal interlocking bolts first. Manually compress the corticotomy. "Perfect circle" free-hand insertion of the distal interlocks is now completed.

Deformity correction can be achieved with tibial Shanz pins placed posterior proximally and distally, with each pin oriented parallel to the adjacent joint. Fixator assisted nailing techniques can be used [23]. Blocking screws should be liberally used to prevent intraoperative deformity and prevent deformity from developing during lengthening (Fig. 9.20a–e).

Intraoperative Nail Testing for All Limb Lengthening Techniques

All nails are tested intraoperatively, before closure, to ensure mechanical function and that subsequent distraction at the osteotomy site will occur postoperatively.

Post-operative Management

Encourage isometric exercises and active range of motion of adjacent joints throughout the lengthening process. Use a cam walker boot to support the foot and ankle in neutral position in tibial lengthenings. Use a knee immobilizer to support full knee extension during femoral lengthenings. Restrict weight bearing to 30 lb pressure maximum until three cortices are evident on X-rays (generally 3–4 months). Oral opiates should be adequate for pain control. Avoid nonsteroidal anti-inflammatory drugs (NSAIDs) beyond the first few days postoperatively, as these agents can slow regenerate bone formation. Consider 2–6 weeks of thromboembolism prophylaxis appropriate to the patient's risk factors. Begin physical therapy, stressing ankle dorsiflexion and knee extension for tibial lengthenings, and knee and hip extension for femoral lengthening. Weekly postoperative physical therapy visits are advised to emphasize the need for continued therapy in preventing contractures in all patients, but most importantly in those with congenital etiologies (Fig. 9.21).

Recommend calcium and vitamin D supplements, and a diet high in protein and carbohydrates, and low in fat. The importance of the latency period must be considered [34]. Latency is commensurate with the patient's age, health, bone being treated, bone quality, location of the corticotomy, and magnitude of the acute correction performed. Generally, the latency period is slightly longer in intraoperatively performed corrections than with gradual corrections, 5–7 days in a child's femur, and 7–10 days in a child's tibia. Adults require latency of 7–10 days in the femur and 10 days in the tibia. Acute rotational and translational corrections require an additional 2 days of latency.

The rate and rhythm of distraction should begin at 0.25 mm every 6 h, and then adjusted based on weekly assessments of the X-ray appearance of the bone regenerate density, volume, contour, and consistency.

Physical therapy sessions and principles previously outlined must be followed [35]. The weekly follow-up visits

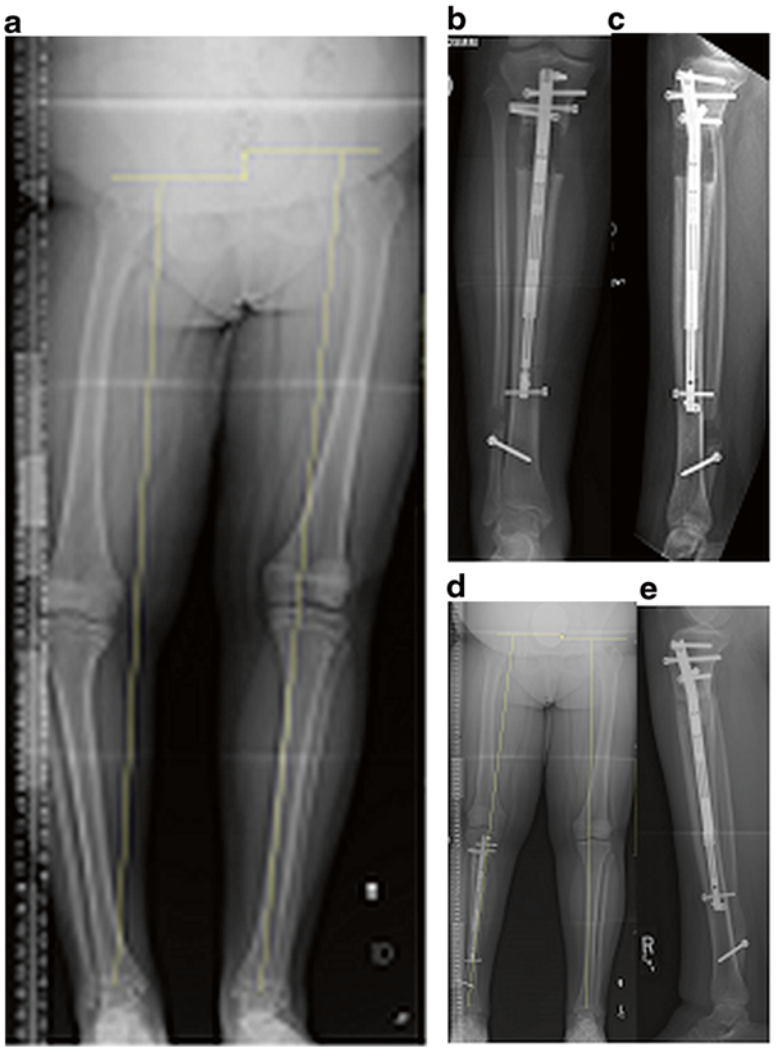

Fig. 9.20 (**a**) Adolescent Blount's with 15° varus, 10° procurvatum, 10° internal rotation, and 3 cm of shortening. (**b**, **c**) Acute interoperative varus, rotation and procurvatum correction with fixator assisted nailing, then gradual lengthening. (**d**, **e**) Deformity correction maintained throughout lengthening by proximal posterior and lateral blocking screws

during the distraction phase can be extended to monthly visits during the consolidation phase. Patients must be informed to prevent contracture, improve motion, and not to exceed the 30 lb weight-bearing restriction during this phase. Full weight-bearing is not allowed until corticalization is radiographically evident on three of four cortices. Physical therapy can be modified to strength and endurance training once three cortices are evident. Removal of the implant is performed 1 year after surgery, provided the regenerate bone is circumferentially corticallized.

Complications of Motorized Intramedullary Lengthening

Little has been written on the subject of complications of motorized limb lengthening, as the technology is so new. Green and Dahl presented a poster exhibit on the subject as it relates to all methods of lengthening at the AAOS annual meeting in 2013 [36]. The authors point out that certain complications of limb lengthening are intrinsic to any bone lengthening, and can occur regardless of the technique or device used.

Limb lengthening complications include:

1. Failures of preoperative assessment
2. Intraoperative complications
3. Incomplete corticotomy
4. Iatrogenic deformity during insertion
5. Premature consolidation
6. Failures of bone formation
7. Device failure
8. Joint contracture
9. Joint subluxation
10. Deformity during lengthening
11. Neurological consequences
12. Muscular consequences
13. Psychological aspects
14. Social/familial aspects

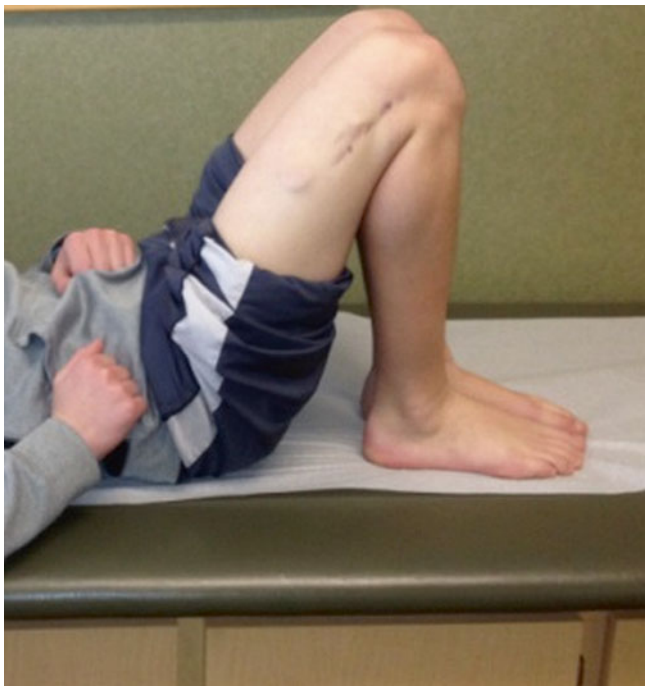

Fig. 9.21 Proper therapy compliance allowed the patient illustrated in Fig. 9.20 to maintain nearly full knee range during treatment

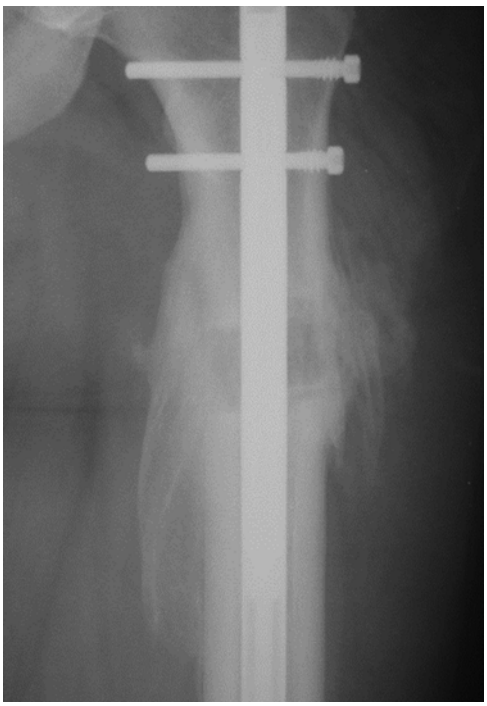

Fig. 9.22 Excessive bone formation in a patient with remote head trauma prevented distraction beyond 2 cm despite increasing the lengthening rate to 1.5 mm/day

15. Fracture after lengthening
16. Deformity after lengthening
17. Stiffness following lengthening
18. Surgical site infection

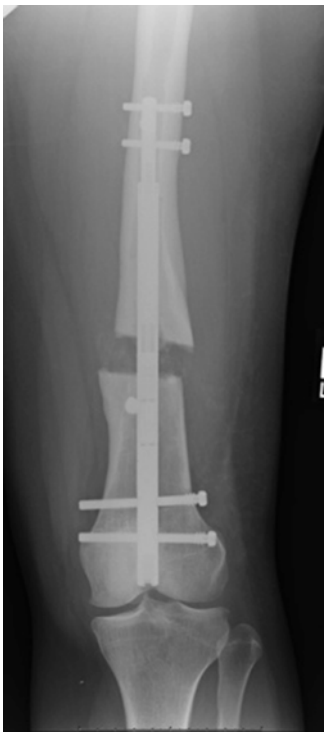

Fig. 9.23 Atrophic regenerate in a multiply operated femur requires a delay and/or slower lengthening rate until the regenerate improves

Pin and wire site infection has been eliminated altogether.

Premature consolidation is most likely to occur in the young patient with femoral lengthening without acute deformity correction. A clue to this occurrence in fixator lengthenings, extreme wire or pin site deflection on X-ray, is not evident in intramedullary lengthenings. A failure of the corticotomy to continue separation at the rate expected signals the clinician to increase the rate of distraction (Fig. 9.22).

Poor new bone formation seems to occur more commonly with intramedullary lengthenings than with fixator lengthenings, as reaming damages the marrow source of regenerate bone, and acute corrections damage the periosteal source of new bone. Atrophic bone formation should be corrected by temporarily stopping the lengthening for 3–5 days, and then resuming the lengthening at a slower rate until the regenerate improves. Delayed healing, primarily in adults, can be expected in 4 % and can be minimized by ideal corticotomy technique, a longer latency period, weekly monitoring of X-rays, and slowing the rate or temporarily stopping the lengthening in the face of poor regenerate. If the regenerate does not improve with these maneuvers, a reversal of the lengthening can be done with PRECICE device. The penalty for continued lengthening in the face of poor regenerate bone is a nonunion, which may require nail exchange and/or bone grafting (Fig. 9.23).

Fractures occurring through regenerate bone should no longer occur, as the nail protects the regenerate bone. Femur

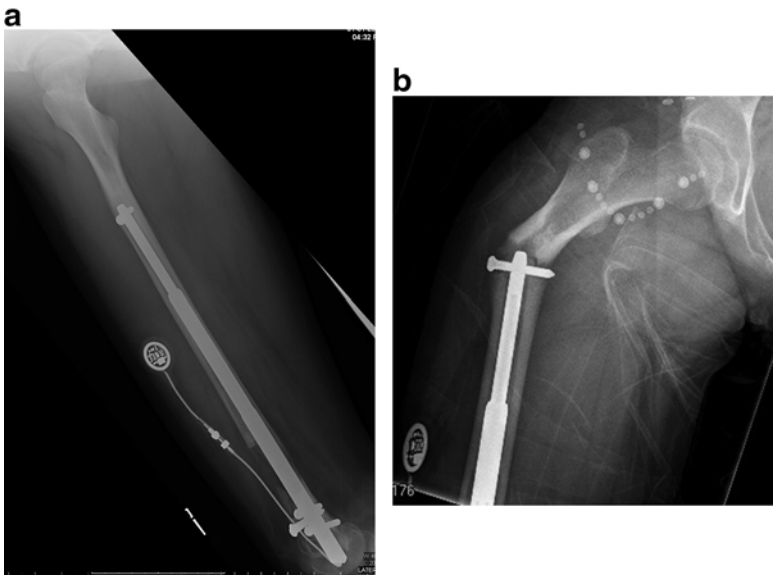

Fig. 9.24 (**a**) This 14-year-old female with congenital short femur required additional reaming, with resulting anterior cortical thinning. (**b**) After completing the lengthening a fracture developed through the proximal locking bolt at the area of maximal cortical thinning on the tension side of the femur

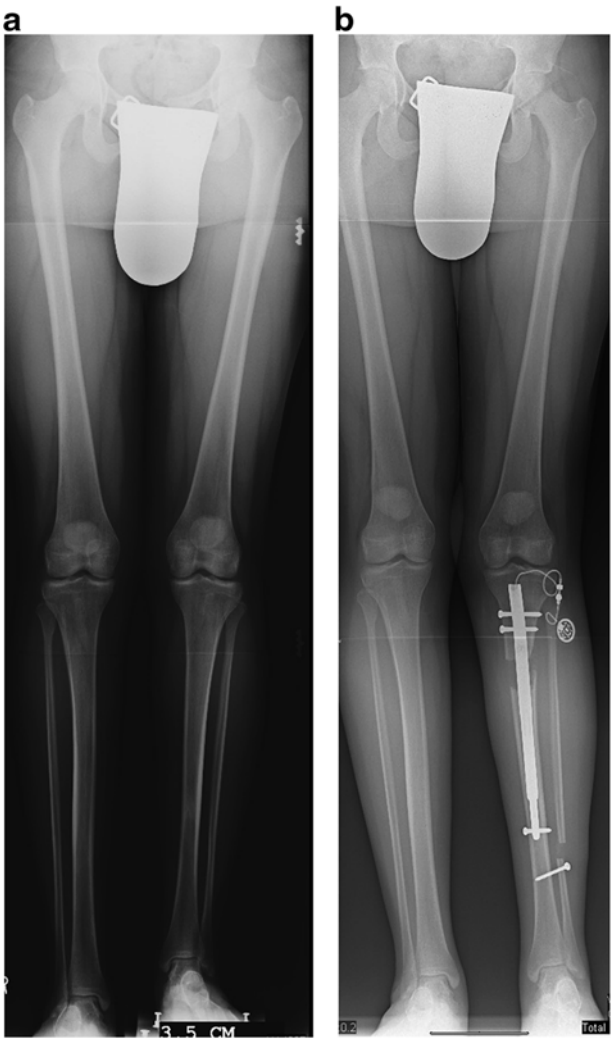

Fig. 9.25 (**a**) Congenital short tibia of 3.5 cm with normal axial alignment. (**b**) Valgus deformity developed during lengthening. Note the large space in the proximal metaphysis allowed the nail to migrate laterally during lengthening

fracture at the tip of a lengthening nail can occur when the bone is too small for the device (children), and excessive or eccentric reaming has occurred to accommodate the nail (Fig. 9.24a, b).

Deformity during distraction, a known complication of fixator lengthening, is at risk to occur in intramedullary lengthenings too. This occurs most commonly in the distal femur or the proximal tibia where the wider metaphyseal bone may allow angulation around an intramedullary nail despite adjacent locking screws. Blocking screws should be placed on the concave side of the anticipated deformity of varus/procurvatum in the femur and valgus/procurvatum in the tibia. Surgical site infection is rare, but deep infection has been reported in a patient previously having undergone prolonged external fixation in the past (Figs. 9.25a, b and 9.26).

Contracture or subluxation of the hip, knee, or ankle in congenital cases can occur, just as in external fixator lengthenings. While doing intramedullary lengthenings in congenital etiology, protection of the knee joint by spanning is not possible, requiring more strict maintenance of the ability to fully extend the knee. The joint dislocation cascade of knee flexion contracture, followed by knee translation, progressing to posterior subluxation, and then to frank dislocation must be prevented at the beginning. Prevention methods require awareness, vigilance, and modest lengthening goals, as these soft tissue complications are intrinsically related to the underlying diagnosis and host condition. Physical therapy directed at stretching, and joint specific static and dynamic bracing are of value as in any lengthening [35]. The ankle joint is protected from equinus deformity by static splinting, stretching, and in certain congenital cases, an extraarticular screw, removed after completion of the lengthening.

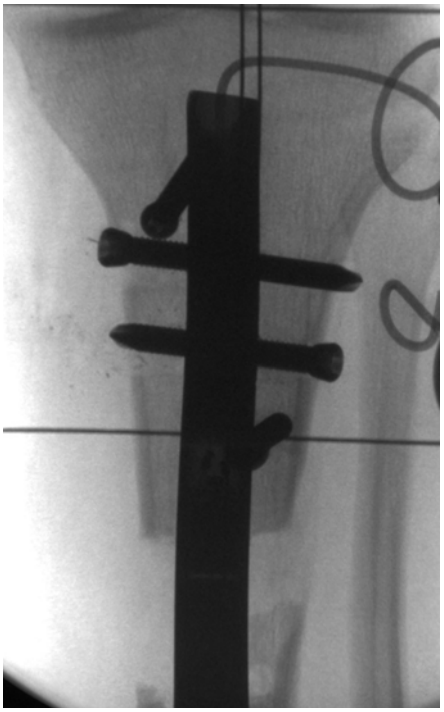

Fig. 9.26 Blocking screws serve to narrow a capacious canal, in this example, correcting proximal tibial valgus

Outcomes

Early clinical case series of the FITBONE and PRECICE devices report favorable outcomes and patient satisfaction, with relatively few implant problems [10, 11, 37]. High accuracy of distraction, maintenance of joint motion, favorable alignment, and fewer complications have been noted, compared with external fixation lengthenings [9].

Patients report significantly lower levels of pain with motorized intramedullary lengtheners, compared with external fixators [38]. Reports of mechanical device failure such as nail breakage of the FITBONE are rare (4 in 2,000 cases) (Roman Stauch, Intens, personal communication). Nail breakage of the PRECICE is reported to be 11/600 and is more common in bilateral applications, as patients with these applications have a greater problem with restricted weight-bearing compliance. Failure to distract is reported in 12/600 with the PRECICE device. Transmitter, receiver, cable, or motor failure of FITBONE is reported to be 16/2,000 (Personal communication, Bart Balkman 2014).

Just as in Ilizarov methodology, proper surgeon education and assembly of a lengthening team of nurses, therapists, and orthotists at centers of excellence cannot be overemphasized.

Summary

Critical to the success of a motorized internal lengthening nail are combining proper surgical training, accurate preoperative planning, minimally invasive surgery, mechanical integrity of the construct, and ideal control of the rate and rhythm of distraction. Early designs that were mechanically actuated had problems with rate control resulting in bone formation complications. The two current designs use either magnetic or electrical control, and have reliable use while eliminating pin and wire complications and fixator-associated pain. While internal lengthening has obvious advantages, there are specific patient indications. Children with open growth plates or small bones are not suitable candidates. External fixation and associated hybrid techniques such as lengthening over nail and plate-assisted lengthening continue to be necessary for certain cases. The correction of severe foot and joint deformities will still require external fixation for the foreseeable future. Improvements in instrumentation and expansion to other conditions will broaden the safety and efficacy of these devices. The motorized intramedullary lengthening nail is an important new tool for the limb length and deformity correction surgeon.

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