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ORIGINAL ARTICLE

Posttraumatic Reconstruction of the Ankle Using the Ilizarov Method

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Abstract Reconstruction of the ankle after trauma requires a variety of treatment strategies. Once the personality of the problem is appreciated, a tailored approach may be implemented. The Ilizarov method provides a versatile, powerful, and safe approach. It is particularly useful in the setting of infection, bone loss, poor soft tissue envelope, leg length discrepancy, bony deformity, and joint contracture. In this article, a variety of posttraumatic ankle pathologies are discussed. Treatment methods including osteotomy, arthrodesis, distraction, correction of contracture, nonunion repair, and tibia and fibula lengthening are reviewed. The use of the Ilizarov method for acute and/or gradual correction as well as the application of simultaneous treatments at multiple levels is discussed in this article.

Key words level of evidence · level V · expert opinion

Introduction

The ankle is particularly vulnerable to trauma. The bones of the ankle are subcutaneous. The soft tissue envelope consists of only skin, tendon, and neurovascular structures anterior, lateral, and medial to the joint. Only in the posterior quadrant is there a modest muscular envelope. In addition, the ankle joint does not tolerate deformity or articular incongruity after trauma. Studies have shown that this leads to pain and progressive ankle arthrosis [1–3].

The soft tissue envelope is a crucial factor in dealing with acute and posttraumatic injury of the ankle. Often the acute injuries are open fractures, which require plastic surgery intervention including skin grafts, and free flaps. Compromise to the soft tissue is a major factor in determining the outcome of high-energy ankle injuries particularly with regard to infection [2, 4].

Tibial nonunions and failed pilon fractures have been treated with a variety of surgical methods including plate osteosynthesis with bone graft [4, 5], intramedullary (IM) nailing [6], and external fixation [7–17]. The complexity of a posttraumatic ankle (PTA) can be quite variable and depends on several factors. The "personality of a fracture" was a term and concept introduced by Shatzker and Tile [18] and its use underscores the complexity of a particular problem and helps organize a treatment approach. It is helpful to apply this personality concept to the PTA. The personality of a PTA is determined by several factors, including joint arthrosis, bone loss, radiographic appearance, and stiffness, as they relate to the nonunion biology, deformity, leg length discrepancy, presence or history of infection, soft tissue envelope, retained hardware, and patient factors including diabetes, smoking, and neuropathy.

The Ilizarov method has gained many advocates for the treatment of tibial nonunions and failed pilon fractures over the last two decades, particularly hypertrophic nonunions [11, 12, 14–16, 19, 20] and nonunions associated with bone loss [13, 21–23], infection [24–27], poor soft tissue envelope [11, 16] and ankle fusion [28–31]. The classic Ilizarov frame (Smith & Nephew, Memphis, TN, USA) has been used to correct all deformity, including lengthening and bone transport [22, 32–36] and fusion [28–31]. However, deformity correction of translation and rotation can be complex and cumbersome with such a frame and require lengthy frame modifications.

The Taylor spatial frame (TSF; Smith & Nephew) is an evolution of the original Ilizarov frame and uses the same concepts of distraction osteogenesis as the classic frame. However, it can be used with the help of a computer program to simultaneously correct length and all aspects of deformity including angulation, translation, and rotation. This is accomplished by establishing a "virtual hinge" in space around which all deformity is corrected. Circular rings are connected with 6 struts, which are gradually adjusted by the patient to correct the entire deformity [9, 16].

We have used this modern Ilizarov method to comprehensively approach these complex,and in many cases, limb

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salvage situations. The acute injuries leading to the need for reconstruction range from low energy ankle fractures to high-energy pilon fractures. A PTA problem can be complex and include numerous factors. These factors will define the personality of the ankle and this will help us establish a tailored and rational treatment approach.

The goals of treatment are a plantigrade foot, optimal leg lengths, bony union, ankle stability, and a mobile painless ankle joint. In many circumstances, the ankle joint is destroyed and an arthrodesis becomes the best option for dealing with pain and/or instability.

Clinical evaluation

In the history, one should obtain information about type of bony and soft tissue injury, surgical procedures performed, history of infection, and the use of antibiotics. High-energy injuries and open fractures have a higher risk for infection. Information about back pain, perceived leg length discrepancy (LLD), use of a shoe lift, and deformity should be elicited from the patient. The presence of deformity will often lead to the patient's report of a feeling of increased pressure on the medial or lateral part of the foot with a valgus or varus deformity, respectively. A short leg will often lead to complaints of low back pain and contralateral hip pain. If antibiotics are being used to suppress an infected nonunion, an attempt should be made to discontinue these for 6 weeks before surgery to obtain reliable intraoperative culture samples. Discontinuation of antibiotics must be done with caution and careful observation, particularly in compromised patients such as those who have diabetes or are on immunosuppressive medications. The current amount of pain, the use of narcotics, and the ability to ambulate with or without support should be noted.

On physical examination, one should look for deformity and LLD with the patient standing still and walking. The inability to bear weight suggests an unstable nonunion. The view from the back is helpful for seeing coronal plane deformity. LLD is evaluated by using blocks under the short leg and by examining the level of the iliac crests. The view from the side is helpful for observing sagittal plane deformity and equinus contracture. The combination of recurvatum deformity above the ankle and equinus contracture of the ankle will lead to a foot translated forward position with an extension moment on the knee (Fig. 1). Range of motion of the ankle, subtalar, forefoot, and toes should be recorded. Rigid compensation for ankle deformity through the subtalar joint is an important factor. This typically occurs when there is long-standing ankle deformity. If this is present, it must be taken into account when correcting the ankle. The condition of the soft tissue envelope, especially previous surgical wounds and flaps, and neurovascular findings should be recorded. This includes the posterior tibial and dorsalis pedis pulses, foot sensation, and dorsiflexion and plantarflexion motor function of the ankle and toes.

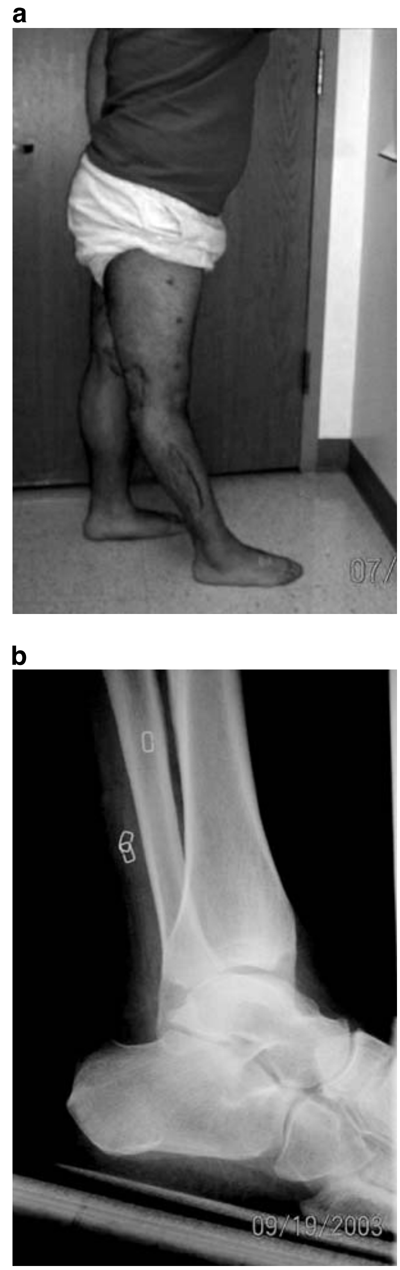

Fig. 1. **a** Side view showing an equinus contracture of the ankle associated with a foot forward position and hyperextension at the knee. **b** Lateral radiograph showing the equinus contracture of the ankle

Radiographs should include anteroposterior (AP), lateral, and mortise views of the ankle, Saltzman's view of both feet [37], and a 51-in. bipedal erect leg x-ray including the hips to ankles with blocks under the short leg to level the pelvis [38]. LLD as well as a limb alignment can be measured from a standing bipedal 51-in. radiograph. The short leg is placed on blocks to level the pelvis and the height of the blocks is recorded. This can be done with the patient using crutches if necessary. These radiographs yield crucial information about LLD, deformity, presence of hardware, arthritis, and bony union. A supine scanogram can also be used to measure length discrepancy but this is not useful for alignment analysis. Computed tomography (CT) scan and magnetic resonance imaging (MRI) can be used for further evaluation as needed. The CT scan can be helpful in getting more information about bony union. The MRI can be helpful for obtaining information about the condition of cartilage in the ankle and subtalar joints and the presence of infection. Nuclear medicine studies can also be used, but we have not found them to be very helpful in this evaluation.

Rotational deformity is best assessed on clinical exam with the patient in the prone position. Thigh-foot axis (TFA) is used to assess rotational deformity of the tibia. Rotational profile of the femur is used to assess rotational deformity in the femur. CT scan can also be used for this purpose. CT scan cuts at the proximal femur, distal femur, proximal tibia, and distal tibia allow analysis of rotational deformity [38].

Laboratory studies including white blood cell count, erythrocyte sedimentation rate, and C-reactive protein level can be helpful for diagnosing the presence of infection. Selective lidocaine injections into the ankle and subtalar joints may be helpful for diagnosing the dominant source of pain.

Classification

The following is a list of PTA personalities that can be addressed with a modular Ilizarov method treatment approach.

1. Ankle arthritis
   (a) With no deformity
   (b) With deformity
   (c) With subtalar arthritis
2. Supramalleolar deformity
   (a) Without ankle arthritis
   (b) With ankle arthritis
3. Ankle contracture
   (a) Without supramalleolar deformity
   (b) With supramalleolar deformity
   (c) With arthritis
4. Supramalleolar nonunion
   (a) Hypertrophic (stiff)
   (b) Normotrophic (partially mobile)
   (c) Atrophic (mobile)
   (d) Infected
   (e) With ankle arthritis
5. Mismatched columns of the ankle
   (a) Tibia short
   (b) Fibula short
6. Associated tibial shaft problem
   (a) Deformity
   (b) LLD
7. Bone loss
   (a) From tibial plafond
   (b) From talus

Treatment principles

Features of the Ilizarov method

The Ilizarov method is particularly useful for addressing this spectrum of posttraumatic ankle pathology. Listed below are versatile features of the Ilizarov method [10, 11].

1. Avoids internal fixation in presence or history of infection.
2. Allows a minimal incision technique in setting of poor soft tissue.
3. Utilizes acute and/or gradual correction of deformity.
4. Utilizes opening wedge correction avoiding need for bone resection.
5. Useful for large deformity correction.
6. Postoperative adjustability for compression or correction.
7. Simultaneous lengthening is possible for optimization of LLD.
8. Allows multiple-level treatment (a modular approach) (Fig. 2).
9. Weight bearing and ankle range of motion are encouraged.

These features will be discussed in relation to the spectrum of the posttraumatic ankle personality.

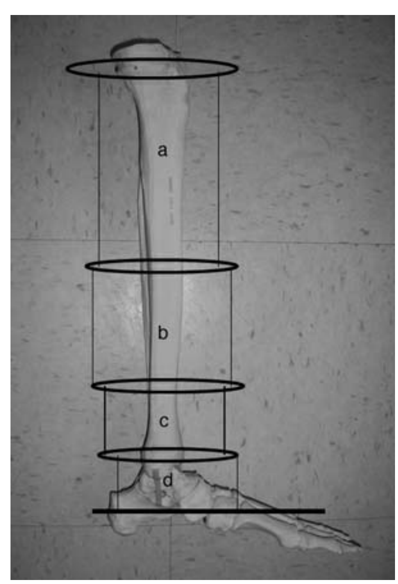

Fig. 2. Schematic drawing depicting the various zones of treatment with the Ilizarov method. **a** Proximal tibia lengthening and/or deformity correction zone. **b** Tibial base consisting of 2 rings. **c** Supramalleolar correction zone. **d** Ankle fusion or contracture correction zone

Acute or gradual correction

One can use either acute or gradual correction of a nonunion or malunion. Acute corrections can be performed in conjunction with all methods of fixation including plates, IM nails, and external fixation frames. Gradual correction requires the use of specialized frames. The personality of the problems helps guide the surgeon toward the best method. For example, a tibial malunion with 15° valgus deformity and 4-cm shortening is best handled with an osteotomy to gradually correct the angular deformity and lengthen the bone with a specialized frame. The Ilizarov method is used to gradually correct the complete deformity with distraction osteogenesis. One may choose to perform the deformity correction and lengthening at one level if bone regeneration potential is good. Alternatively, one may choose to perform a double-level osteotomy—one level at the center of rotation and angulation (CORA) [38, 39] for deformity correction and one level for lengthening in the proximal tibia metaphysis. Gradual correction achieves treatment of shortening and carries less risk of peroneal nerve stretch neuropraxia than if attempted with an acute correction.

The use of plates and IM nails requires an acute correction of angular and translational deformity. Acute corrections are particularly useful for modest deformity correction, mobile atrophic nonunions that are opened and bone grafted, and small bone defects that can be acutely shortened. The principal advantage of acute correction is earlier bone contact for healing and more simple fixation construct. Acute corrections are generally better tolerated in the femur and humerus and less well tolerated in the tibia and ankle related to issues of neurovascular insult [11, 38].

Gradual correction with a specialized frame is useful for large deformity correction, associated limb lengthening, bone transport to treat segmental defects [13, 21–23], and stiff hypertrophic nonunion repair [11, 12, 14–16, 19, 20]. Gradual correction uses the principle of *distraction osteogenesis* commonly referred to as the *Ilizarov method* [10, 11]. Bone and soft tissue is gradually distracted at a rate of approximately 1 mm/d in divided increments. Bone growth in the distraction gap is called *regenerate*. The interval between osteotomy and the start of lengthening is called the *latency phase* and is usually 7 to 10 days. The correction and lengthening is called the *distraction phase*. The *consolidation phase* is the time from the end of distraction until bony union. This phase is most variable and is most affected by patient factors such as age and health. If the *structure at risk* is a nerve such as the peroneal nerve for a proximal tibia valgus deformity or the posterior tibial nerve for an equinovarus deformity of the ankle, gradual correction may be the safer option. The correction can be planned so that the structure at risk is stretched slowly [10, 11, 38]. If nerve symptoms do occur, the correction can be slowed or stopped. Nerve release can be used in select situations based on the response to gradual correction [38].

Treatment options

Ankle arthritis

If the ankle is very stiff and painful, then arthrodesis becomes the most predictable option. Although this type of arthrodesis can be done with an Ilizarov frame, it can be successfully performed more simply using screw fixation. There may be some indication for total ankle replacement in a very select group of patients, namely, the older patient with no history of infection (Table 1).

If the ankle has an arc of at least 30° of motion, the arthritis is moderate, and the patient is not interested in pursuing fusion, then distraction arthroplasty may be a good option. This technique was popularized in the Netherlands and involves placing an external fixation frame across the ankle. Encouraging results have been reported at intermediate term follow-up [40]. Joint distraction is based on the concept that osteoarthritic cartilage has some reparative activity when there is a release of mechanical stress on the cartilage while intra-articular intermittent fluid pressure is maintained [41]. Our current joint preservation approach includes arthroscopic debridement, anterior exostosis removal, and percutaneous tendo Achillis lengthening (TAL) if these are indicated. In addition, we apply an articulated distraction frame to allow ankle range of motion and the ability to correct contracture in addition to the distraction [42] (Fig. 3). This frame is worn by the patient for 3 months. Weight bearing and ankle motion are encouraged throughout the treatment. Results with this treatment both clinically and radiographically, with an increased joint space, have been encouraging. This treatment does not burn bridges for a possible future need for arthrodesis or ankle replacement. If there is ankle deformity, the distraction can be combined with a supramalleolar osteotomy by adding another level to the frame (Fig. 4).

When there is deformity with its apex at the ankle, correction is done through the fusion. Acute correction is accomplished with removal of a medial or lateral wedge from the plafond for correction of valgus or varus deformity, respectively. Acute correction must be performed with caution and vigilance for neurovascular insult. The Ilizarov frame is very useful in stabilizing flat bony surfaces that lack the congruity of a simple ankle fusion (Fig. 5). Gradual correction is a safer option in setting of large deformity. The prepared ankle fusion site is gradually positioned neutral with the use of a dynamic Ilizarov/Taylor spatial frame.

When both ankle and subtalar joints are affected, there may be an indication to fuse both joints. Selective lidocaine injections of both joints under fluoroscopy can prove useful for preoperative decision making. Both ankle and subtalar joints are prepared for fusion and the Ilizarov frame can be used for compression arthrodesis.

Supramalleolar deformity

In the absence of symptomatic arthritis, correction of the deformity with a supramalleolar osteotomy is performed

Table 1. Summary of evaluation and treatment

Classification	Evaluation	Treatment	Technical pearls/frame configuration
Ankle arthritis			
no deformity	Good mobility	Ankle distraction	Hinges at ankle axis
	Poor mobility	Ankle fusion	Screw fixation
with deformity	Magnitude and time duration of deformity	Arthrodesis with I/TSF, acute or gradual	Wedge excision for acute correction; I/TSF for gradual correction, need talus wire
subtalar arthritis	MRI and lidocaine joint injections for diagnosis	Tibio-talo-calcaneal arthrodesis with I/TSF	Compression frame with no talus wire
Supramalleolar deformity			
without arthritis	Check position/mobility of subtalar joint	Supramalleolar osteotomy	I/TSF for acute or gradual correction depending on magnitude and complexity of deformity
with arthritis	Anticipate correction that can be achieved through ankle fusion	Supramalleolar osteotomy with simultaneous ankle fusion	2-Level I/TSF: acute correction of ankle fusion and gradual correction of osteotomy
Ankle contracture			
without bony deformity	Distinguish Achilles contracture vs. gastrocnemius	I/TSF with hinges at ankle; gradual correction; percutaneous TAL	Axis of ankle from tip medial malleolus to tip of lateral malleolus through the talus
with bony deformity	Foot may appear plantigrade because of compensation	Supramalleolar osteotomy with simultaneous gradual contracture correction	2-Level frame; gradual correction at both levels
with arthritis	Pain, stiffness	Gradual correction of prepared ankle fusion if contracture large	Prepare fusion; partial correction acutely and use I/TSF to gradually correct rest of contracture
Supramalleolar nonunion			
stiff	Hypertrophic appearance on x-ray; rule out infection	Do not open nonunion; gradual correction with I/TSF	Osteotomy of fibula needed; then test tibial stiffness
partially mobile	Normotrophic appearance on x-ray; rule out infection	Minimal exposure of nonunion to open canals and bone graft. Then apply I/TSF	Do partial correction in OR but do rest gradually and then compress with I/TSF
mobile	Atrophic appearance on x-ray; rule out infection	Open nonunion site, bone graft and do acute correction; compression with frame	Hold acute correction of nonunion with temporary wires and then apply compression I/TSF
infected	Check for draining sinus	Resect dead infected bone. Antibiotic beads; no bone graft	Choice of acute shortening of defect or placement of beads. Compression with frame
with arthritis	CT scan or MRI helpful to diagnose 2 levels; rule out infection	Compression of nonunion and ankle arthrodesis	2-Level I/TSF with compression of both nonunion and ankle fusion
Mismatched columns of ankle			
tibia short	Healed fibula with settling of tibia; distinguish malunion from nonunion	Gradual correction and lengthening of tibia relative to fibula	Do not place a tibiofibular wire to allow movement of tibia relative to fibula
fibula short	Valgus deformity with lateral tilt of talus	Gradual lengthening of fibula	Use monolateral frame to lengthen fibula and then insert syndesmosis screws to maintain correct position; need to fix tibia to fibula proximally
Associated tibial shaft involvement			
deformity	The tibial shaft deformity is usually source of ankle pathology	Correct tibial deformity and ankle pathology simultaneously	2-Level I/TSF; choice of acute or gradual correction at both levels; goal is straight tibia and plantigrade foot
LLD	Evaluate LLD with blocks and 51-in. erect leg x-ray	Lengthen tibia and approach ankle simultaneously	2-Level I/TSF; gradual lengthening of tibia; acute or gradual correction of ankle; goal with fusion-LLD of 1 cm
Bone loss			
from plafond	Use long x-ray to calculate the longitudinal defect (x-ray defect + LLD); history of or active infection	Bone transport ankle fusion or acute shortening at ankle fusion followed by gradual tibia lengthening	2-Level I/TSF; acute shortening of no more than 2 cm; monitor pulses; neurovascular risk; fashion surfaces of tibia and talus for good contact
from talus	History of or active infection; infected talus with osteonecrosis	Tibiocalcaneus fusion; option of simultaneous tibia lengthening or shoe lift	Prepare tibia and calcaneus surfaces for optimal contact; neurovascular risk with acute shortening; option of acute or gradual shortening; 2-level I/TSF if tibia lengthening is done

I/TSF, Ilizarov/Taylor Spatial Frame (Smith & Nephew, Memphis, TN, USA); TAL, tendo Achillis lengthening; OR, operating room; LLD, leg length discrepancy

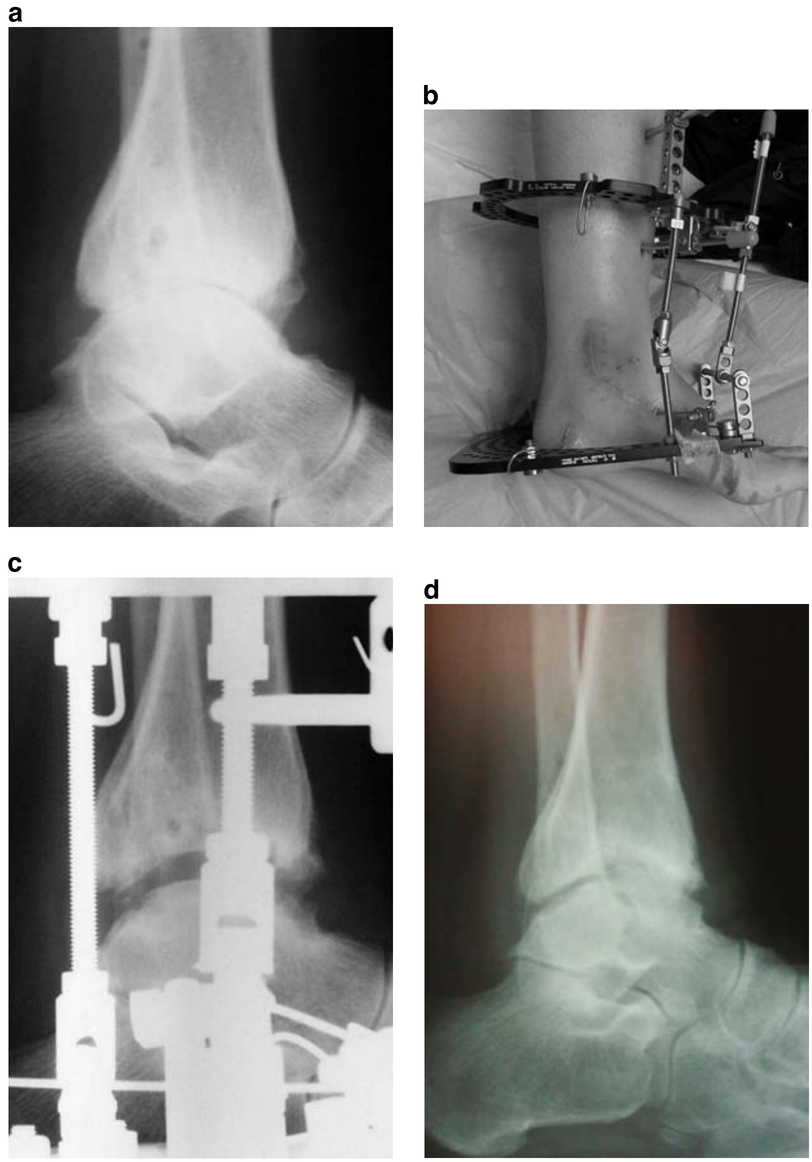

Fig. 3. **a** Lateral radiograph of ankle showing arthritis with no deformity. **b** Side view of an ankle distraction frame with hinges at the axis of the ankle. **c** Lateral radiograph showing distraction of the ankle. **d** Lateral radiograph of the ankle 6 months after frame removal showing an increased joint space. Clinical symptoms were significantly improved

(Fig. 6). The goal is to correct the deformity in both the coronal and sagittal planes and to achieve a lateral distal tibial angle of 90° and an anterior distal tibial angle of 80° [38, 39]. The use of the Ilizarov/Taylor Spatial Frame is particularly useful for a gradual correction of a simple or large oblique plane deformity.

In the presence of symptomatic arthritis, this may be addressed as well. As mentioned earlier, an ankle distraction can be done distal to the supramalleolar osteotomy with the addition of another level of treatment. If the arthritis is severe and symptomatic, the deformity correction can be done simultaneously with an ankle arthrodesis (Fig. 7). Typically, the arthrodesis would be positioned acutely, and simultaneous gradual correction of the osteotomy would continue above the ankle. If there is a large ankle contracture, the option of gradual correction through the prepared ankle fusion may also be used.

Ankle contracture

The usual contracture is equinus. If it is small, acute correction with TAL may be used. If the contracture is large and especially if it is long-standing, it may be safer to do the correction gradually. After a percutaneous TAL, an Ilizarov frame is applied across the ankle and hinges are placed in line with the axis of the ankle [38]. This is a doubly oblique plane that passes from the tip of the lateral a

b

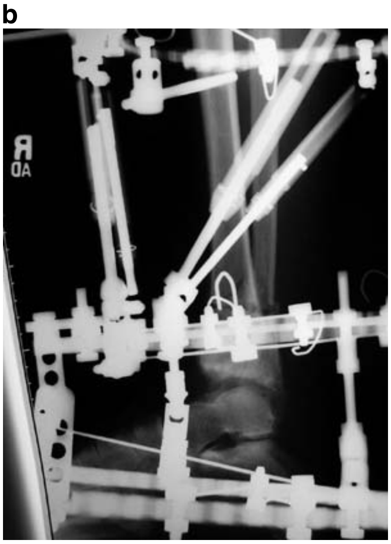

Fig. 4. a, **b** Side view and x-ray of a patient who underwent a supramalleolar osteotomy for deformity correction and simultaneous ankle distraction

malleolus to the tip of the medial malleolus through the center of the talus (Fig. 8). The TSF and a virtual hinge may also be used. Correction of the contracture is accomplished by gradually moving the rings parallel to each other. Use of a constrained frame with hinges prevents compression of the ankle articular surfaces during the correction. The posterior tibial nerve is undergoing stretch within the tarsal tunnel during this correction. The gradual approach allows the speed of the correction to be adjusted accordingly and decreases the likelihood of a stretch neuropraxia. If signs and symptoms of stretch neuropraxia are present despite slowing the correction, then a tarsal tunnel release is performed.

Associated supramalleolar deformity may be addressed at the same time. A common presentation is a recurvatum deformity above the ankle combined with an equinus contracture of the ankle. The foot appears plantigrade and anteriorly translated. Acute or gradual correction of both the bony deformity above the ankle and the contracture of the ankle can be accomplished with a 2-level Ilizarov/Taylor Spatial Frame (Fig. 9).

If there is associated arthritis of the ankle, this can be addressed with either a simultaneous fusion or a distraction. This depends on the severity of the arthritis and the physician/patient decision for joint preservation or fusion.

Supramalleolar nonunion

An excellent application of gradual correction is for a hypertrophic stiff nonunion with deformity. This type of nonunion has fibrocartilage tissue in the nonunion and has biologic capacity for bony union. It lacks stability and axial alignment. Gradual distraction to achieve normal alignment results in bone formation (Fig. 10). The nonunion acts like regenerate and bony healing occurs. Modest lengthening of no more than 1.5 cm should be done through the nonunion. If additional lengthening is needed, a second osteotomy for lengthening is performed. Several studies have confirmed Ilizarov's success with this technique [11, 12, 14–16, 19, 20]. The principle advantages are the option of not having to open the nonunion site in the face of poor skin and widened callus and the gain in length through an opening wedge correction. This is particularly beneficial to the region above the ankle where the soft tissue envelope is often compromised. This technique is not useful for mobile atrophic nonunions and less applicable to infected nonunions.

Atrophic nonunions (Fig. 11a) have fibrous tissue at the nonunion site and tend to be mobile. This is often the situation after previous open surgery wherein surgical exposure may have compromised the bone healing biology. Treatment needs to be directed toward improving both the biology and the mechanical environment to achieve bony union. Normotrophic nonunions have both fibrous tissue and fibrocartilage and are partially mobile (Fig. 11b). Atrophic and even normotrophic nonunions should be exposed, bone ends should be contoured so there is healthy bleeding bone on both sides with good contact, and IM canals should be opened. Stripping of soft tissue should be performed within moderation. Acute correction of deformity should be followed by bone grafting and stable fixation with compression. This can be accomplished with a plate, IM nail, or a frame depending on surgeon preference and location. Compression plating of aseptic nonunions has been used successfully [5]. In contrast to acute fracture treatment wherein rigid stability is not necessarily the goal [43], the goal for stabilization of nonunions should be a relatively rigid construct [5, 11].

Circular external fixation can also be useful for atrophic and normotrophic nonunions. In the case of an atrophic nonunion, the frame is used for stabilization after acute correction and an open approach. A positive feature of using a frame is that in addition to the ability to acutely compress the nonunion in surgery, one can add more compression during the postoperative period. The frame is also stable enough to allow full weight bearing right after surgery [11, 17, 25]. Normotrophic nonunions can also be

Fig. 5. **a** AP x-ray showing posttraumatic arthritis of the ankle with varus deformity after a pilon fracture. **b** AP x-ray showing the tibiotalar junction under compression in an Ilizarov frame. Acute correction of the deformity was performed. **c**, **d** AP and lateral x-ray of the ankle 6 months after surgery showing a successful ankle fusion

approached in another fashion with the use of gradual correction. The nonunion can be approached in a minimally invasive fashion through 1- to 2-cm incisions. With the aid of intraoperative fluoroscopy, the nonunion can be mobilized with an osteotome and the IM canals can be opened by using a cannulated drill and curettes. Bone graft can then be inserted. The frame is then applied and used to gradually correct the deformity (angulation and translation). Once this is accomplished, axial compression is then performed. Full weight bearing is allowed immediately after surgery. If additional length is needed, an osteotomy for gradual lengthening can be performed at a different site.

Nonunions after tibial pilon fractures can result in metaphyseal nonunion combined with ankle arthrosis (Fig. 12). Infection, poor soft tissue, and retained hardware often complicate these situations. Treatment should be directed toward repair on the distal tibia, correction of deformity, and ankle arthrodesis if necessary. This can be accomplished with internal [5] or external fixation [28–30]. If bone resection is needed as in the case of infection, then

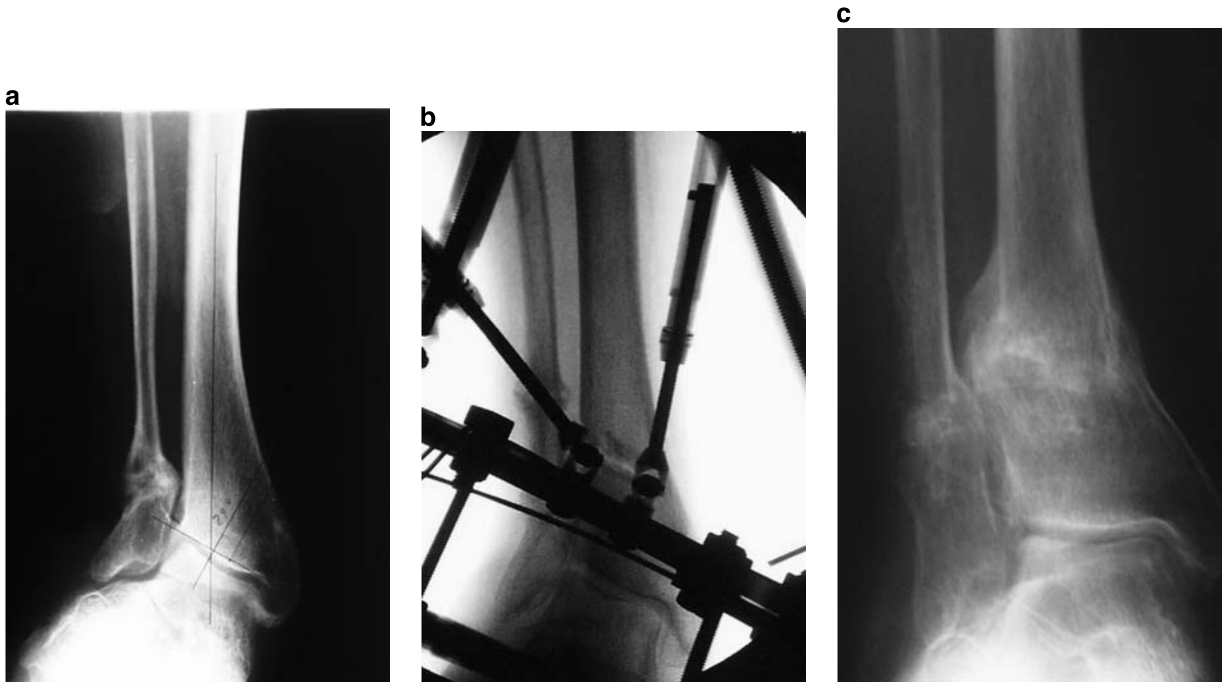

Fig. 6. **a** Malunion with valgus deformity of the tibial plafond in a patient with rheumatoid arthritis. **b** After application of Ilizarov/Taylor Spatial Frame and percutaneous supramalleolar osteotomy. **c** After healing of the opening wedge correction obtained with distraction osteogenesis

ankle fusion and simultaneous tibia lengthening can be done with the Ilizarov method [11, 31].

Infection

Infected nonunions are most complex. Typically, these are atrophic and mobile; however, they can also be stiff and hypertrophic. Infected nonunions should typically be approached in an open fashion. The goals of surgery are to remove all dead bone, open the IM canals, oppose bleeding bone surfaces, and correct the deformity. The patient should ideally have been off all antibiotics for several weeks and multiple intraoperative cultures and

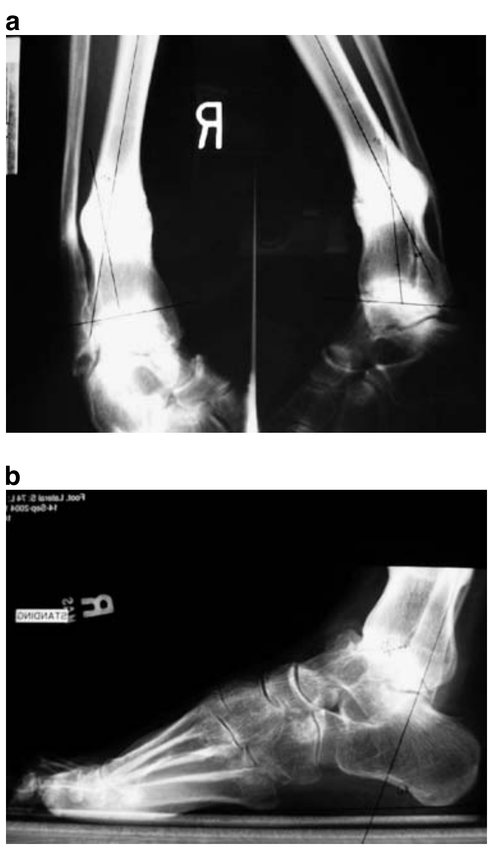

Fig. 7. **a** AP and lateral radiographs showing a patient with a varus, recurvatum malunion with associated ankle arthritis. **b** Lateral x-ray of the ankle showing the advanced ankle arthrosis combined with equinus contracture of the ankle

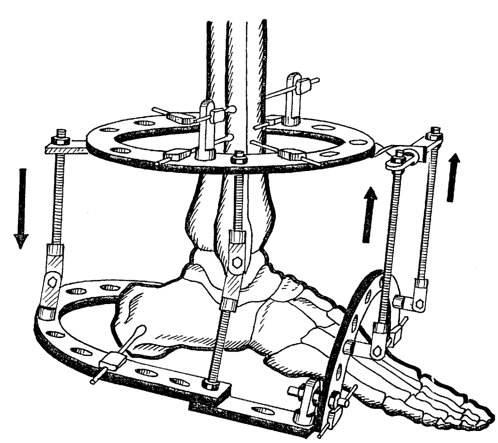

Fig. 8. Schematic drawing showing a constrained frame for gradual correction of an equines contracture. Note the hinges at the ankle

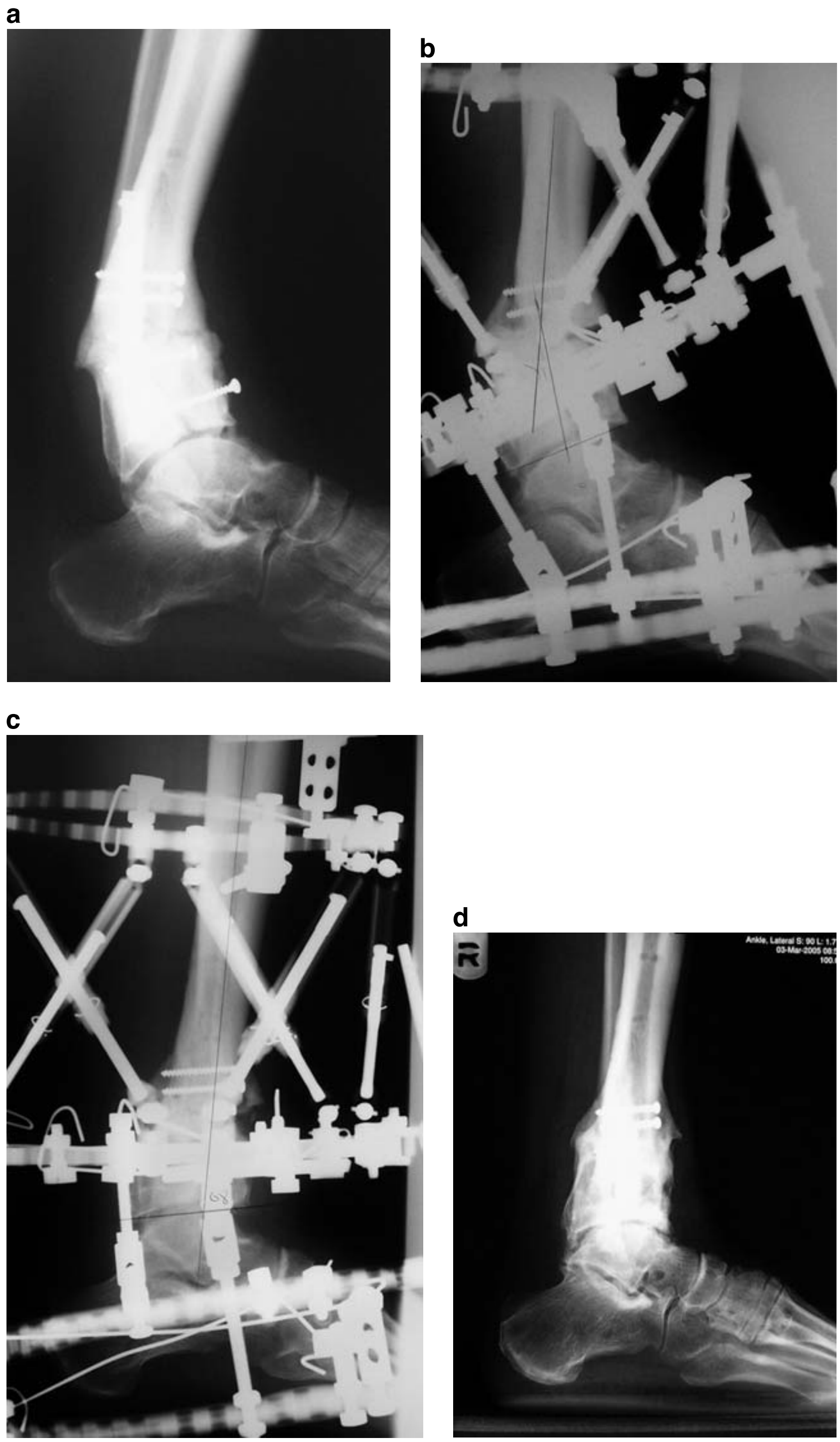

Fig. 9. **a** Lateral x-ray showing a recurvatum deformity of the distal tibia with equinus contracture of the ankle. **b** Postoperative lateral x-ray showing a frame with potential for correction of the supramalleolar deformity and the ankle contracture. **c** Lateral x-ray 6 weeks later showing the correction. **d** Lateral x-ray 1 year later

pathology specimens are sent to the laboratory at the time of surgery. The nonunion is then mechanically stabilized. With the help of an infectious disease consultant, treatment of chronic osteomyelitis is rendered. This usually consists of culture-specific intravenous antibiotics for 6 weeks followed by an oral regimen. Removal of dead bone is needed to eradicate infection. Bone graft should not be used at the primary surgery. Antibiotic beads can be used for dead space management and local antibiotic delivery. Several weeks later, the beads can be removed and the nonunion can be bone grafted. The use of absorbable antibiotic beads made of calcium sulfate has been advocated by some to

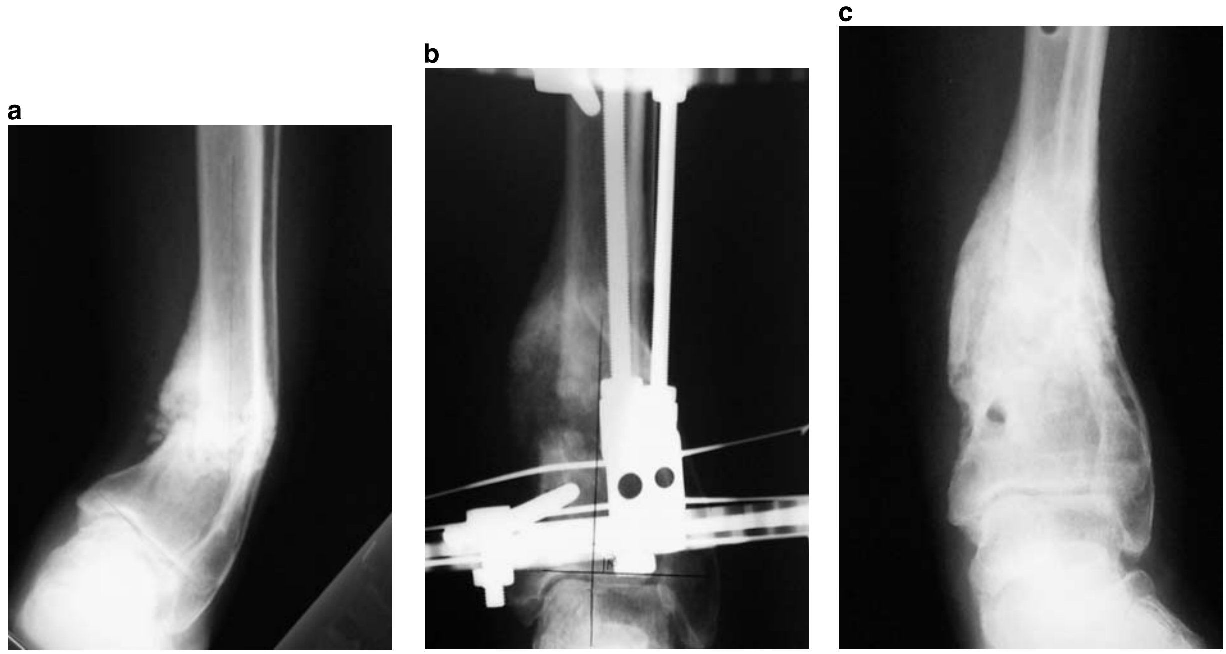

Fig. 10. **a** AP x-ray showing a stiff nonunion with large varus deformity in a blind diabetic patient. This patient had a lateral ulcer at the apex of the fibula deformity. **b** Four weeks after application of the Ilizarov frame. The nonunion was not exposed and gradual distraction correction was performed. **c** Six months after frame removal showing healed nonunion without deformity

avoid the need for removal and subsequent bone grafting [44]. If acute shortening is performed and there is little dead space or purulence, antibiotic beads are not used.

Stabilization can be accomplished with a plate, IM rod, or an external frame. All of these methods have been used successfully; however, internal fixation has the disadvantage of adding foreign material to the infected site and is fraught with risk. The use of external fixation is my preferred approach in most cases of infection. It has the advantage of not adding foreign material to the infection site and can be used to treat more complex situations. If debridement of the nonunion results in a bone defect, the

Fig. 11. **a** AP x-ray of an atrophic mobile nonunion of the distal tibia/fibula with deformity and retained hardware. **b** AP x-ray showing a normotrophic partially mobile nonunion with retained IM nail and valgus deformity

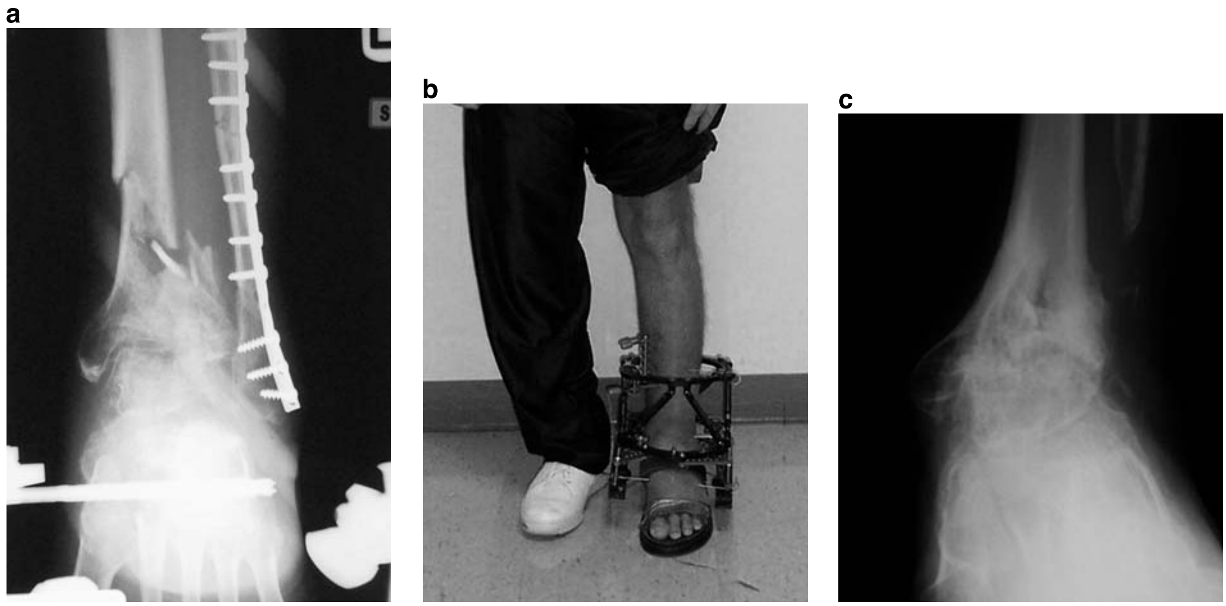

Fig. 12. **a** AP x-ray showing a pilon fracture nonunion 9 months after trauma associated with advanced ankle arthrosis. This patient had been non-weight-bearing in ankle spanning frame for 9 months. **b** Front standing view showing an Ilizarov/Taylor Spatial Frame being used for simultaneous compression of the plafond nonunion and the ankle arthrodesis. **c** AP radiograph 9 months after frame removal showing bony union

frame can be used for *bone transport* (Fig. 13) or acute shortening and gradual lengthening [11, 22, 27, 32].

Staging treatment

Staging the treatment is an important strategy for nonunion management. In case of infection, antibiotic beads may be removed after several weeks and bone graft inserted. In the situation of bone debridement resulting in a bone defect, one may choose to do a gradual or acute shortening with a frame. An osteotomy for lengthening can be done several weeks later after the infection is cleared and after the patient and surgeon have decided on the option of lengthening vs the use of a shoe lift. This has the advantage of protecting the osteotomy site from contamination. In addition, it is often difficult to predict the precise amount of bone resection needed. Once this is known, the patient and surgeon can make a more informed decision about lengthening.

When bone transport is used to treat a bone defect, the docking site should be prepared when there is about 1 cm of gap. Preparation of the docking site includes debridement of fibrous tissue, realignment of bone ends to maximize bony contact and minimize deformity, and addition of bone graft. This improves the rate of bony union [22].

If the soft tissue coverage is poor, flap coverage [24, 27]or the use of a vacuum-assisted closure [45, 46] device may be needed. A staged approach with the plastic surgeon can be helpful. For example, one may do a debridement of bone and soft tissue and apply a simple frame that allows your plastic surgeon access to the wound. After flap coverage has been accomplished, one can then go back and perform bone transport for a bone defect or elevate the flap after several weeks and bone graft the nonunion site.

Mismatched columns of the ankle

The tibia may shorten relative to the fibula. This can be observed as a nonunion or malunion of the tibial plafond. This will lead to abnormal stress transmission across the ankle and premature arthritis [3]. In a normal situation, a transmalleolar line will intersect a middiaphyseal line of the tibia at 83° [38]. Variation from this measurement signifies shortening of the tibia or fibula. This may present after treatment of a pilon fracture with fibula plating and spanning external fixation and percutaneous screws for the tibia. The fibula heals out to length and the tibia settles with relative shortening and varus deformity. Treatment consists of lengthening and correction of the tibial deformity relative to the fibula. This is accomplished with an Ilizarov frame with the distal leg ring fixed to only the tibia and not the fibula. This setup provides the potential for relative lengthening of the tibia through an osteotomy in the case of a malunion or through the nonunion itself (Fig. 14).

Alternatively, the fibula may shorten relative to the tibia. This will occur if the fibula is initially fixed short immediately after the trauma or if it is not fixed and gradually shortens during healing. In this situation, fibula lengthening may be accomplished gradually with distraction osteogenesis. Once the length is correct, syndesmosis screws can be inserted to maintain the length and the frame is removed [47] (Fig. 15).

Associated tibial shaft problem

An example of this would be malunion of the tibia that is associated with ankle arthritis. Recurvatum deformity of

Fig. 13. **a** Lateral x-ray showing an infected nonunion of the distal tibia. **b** Intraoperative x-ray after resection of dead infected bone. Note the 8-cm defect. **c** Standing front view showing a bone transport Ilizarov/Taylor Spatial Frame. **d** AP radiograph 3 months after frame removal showing a successful bone transport with 8 cm proximal tibia lengthening and healed docking site at the distal tibia

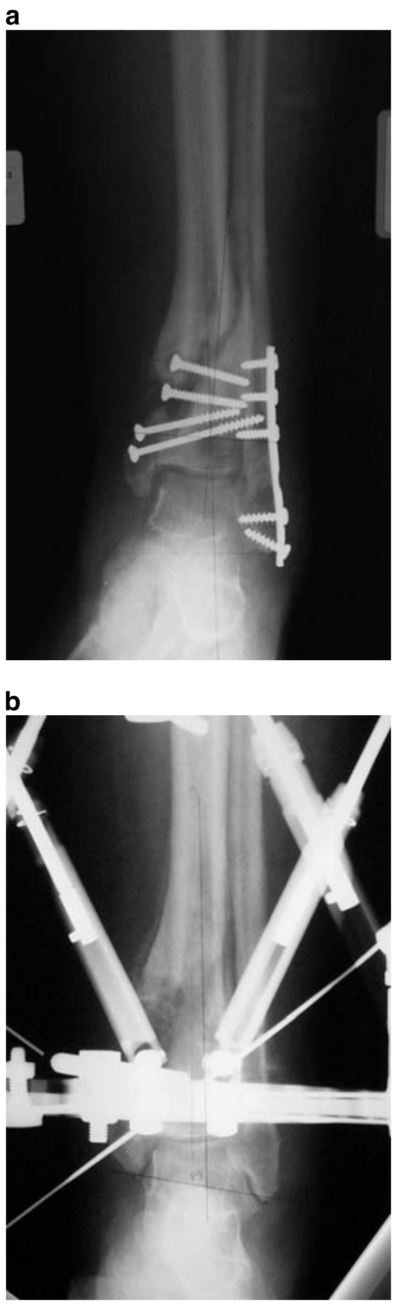

Fig. 14. **a** AP radiograph showing relative shortening of the tibia and a nonunion. **b** After gradual lengthening and deformity correction of the tibia with an Ilizarov/Taylor Spatial Frame

the tibia will lead to uncovering of the talus, abnormal forces across the ankle, equinus contracture, and arthritis. Two-level Ilizarov treatment can be used to correct the tibial deformity and achieve ankle fusion with acute or gradual correction (Fig. 16). If there is shortening of the tibia, this can be addressed at the same time as the deformity correction at the apex of the deformity. An osteotomy [48] at the proximal tibia for lengthening can be done if the bone healing potential at the apex of deformity is not optimal (Fig. 17).

Bone loss

Bone loss from the tibia plafond is the result of the trauma or subsequent infection. This may be associated with the need for an ankle fusion. If a fusion is needed, then a bone transport ankle fusion is done (Fig. 18). Alternatively, acute shortening and fusion of the ankle is done, and gradual lengthening of the tibia follows [31]. In case of infection, there is an advantage to delaying the proximal tibia lengthening for a few weeks. This allows treatment of

Fig. 15. **a** AP x-ray showing relative shortening of the fibula. **b** After fibula lengthening and insertion of syndesmosis screws

Fig. 16. **a** Lateral x-ray showing a recurvatum malunion of the tibial shaft associated with arthrosis and contracture of the ankle. **b** Lateral x-ray of the ankle. **c** Lateral x-ray showing a 2-level frame with correction of the tibia deformity and ankle arthrodesis. **d** Lateral x-ray 6 months after frame removal showing bony union and correction of deformity

the infection with culture-specific antibiotics, a better appreciation for the amount of lengthening that is needed, and a safer environment for the proximal tibia lengthening with less chance of contamination.

Bone loss from the talus can be the consequence of necrosis and osteomyelitis. This can lead to the need to remove the talus. Ankle fracture in a neuropathic patient can lead to a Charcot ankle with collapse and destruction of the talus. In either situation, a tibia to calcaneus ankle fusion is needed. This will usually lead to about 4 cm of shortening. Since 1 cm of shortening is desirable with an ankle fusion, the patient can undergo a simultaneous 3-cm proximal tibia lengthening or use a shoe lift. The tibia to calcaneus contact can be achieved acutely or gradually (Fig. 19). Gradual shortening is safer in terms of neurovascular insult.

Surgical techniques

The Ilizarov/Taylor Spatial Frame can have several levels as needed including proximal tibia, middle tibia, talus, and

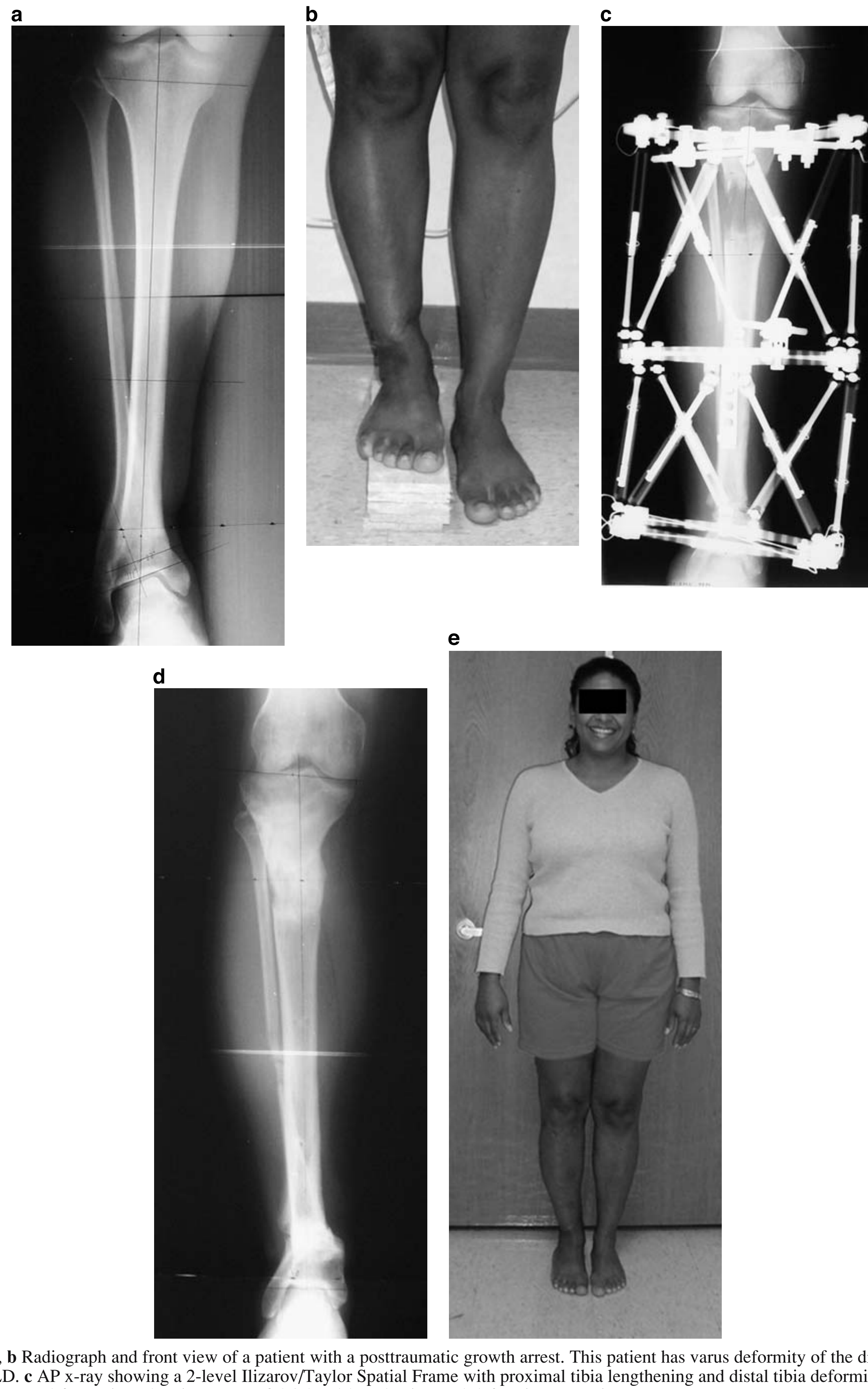

Fig. 17. **a**, **b** Radiograph and front view of a patient with a posttraumatic growth arrest. This patient has varus deformity of the distal tibia and 6 cm of LLD. **c** AP x-ray showing a 2-level Ilizarov/Taylor Spatial Frame with proximal tibia lengthening and distal tibia deformity correction. **d**, **e** AP x-ray and front view showing successful 2-level lengthening and deformity correction

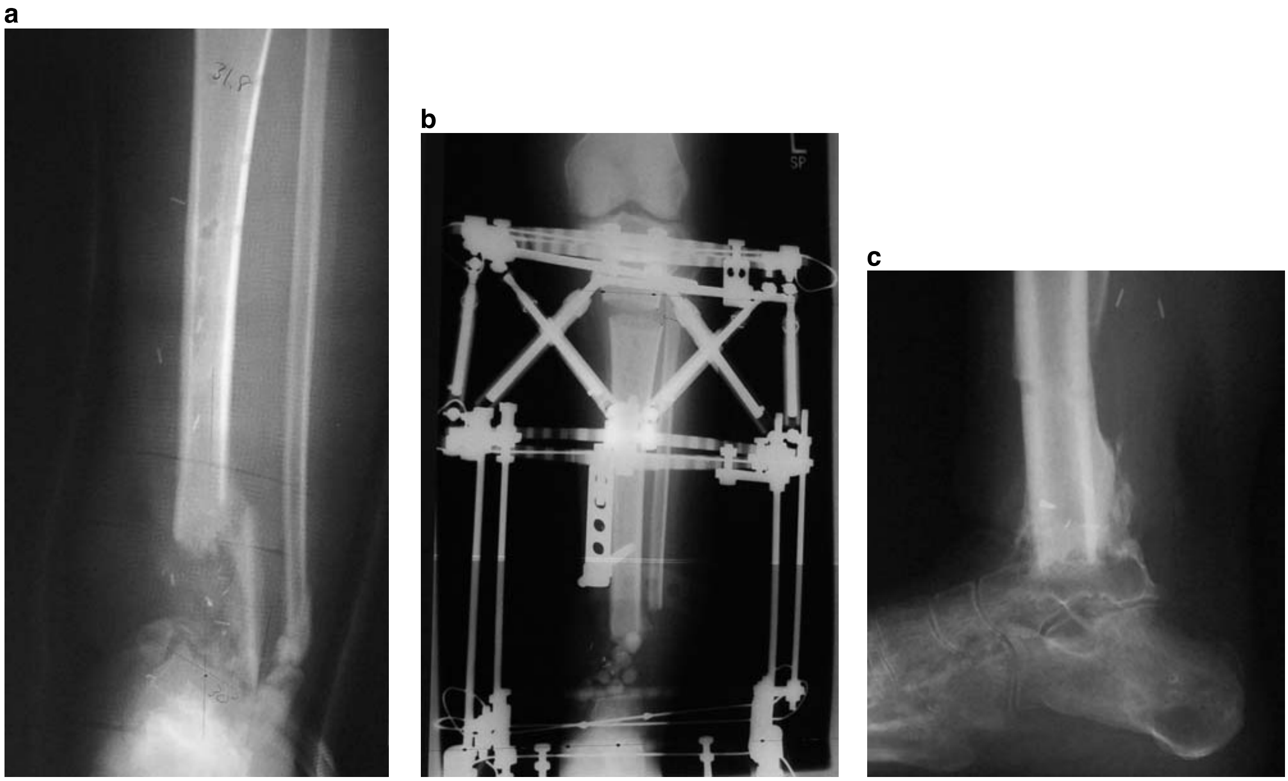

Fig. 18. **a** AP radiograph showing an infected nonunion bone defect of the distal tibia and articular surface. **b** AP radiograph showing a 2-level frame for proximal tibia lengthening and gradual shortening of the defect and ankle fusion. **c** Lateral x-ray showing a successful ankle fusion. A 10-cm proximal tibia lengthening was performed on this patient

calcaneus. The number of levels used depends on the personality of the PTA (Fig. 2). A base of typically 2 rings is placed along the axis of the middle tibia. Each ring is usually fixed with 2 points of fixation with 1.8-mm smooth tensioned wires and/or 6-mm half pins (Fig. 20). This can be modified to one ring if less fixation is needed. The remainder of the construct depends on the particular situation. A distal tibia ring is used for a supramalleolar osteotomy. A foot ring with hinges is used for ankle distraction or contracture correction. A foot ring with

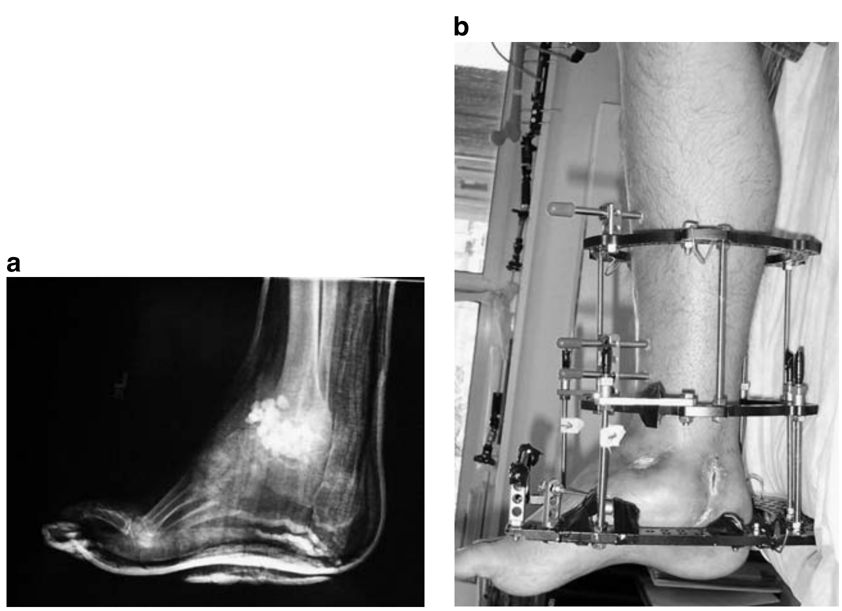

Fig. 19. **a** Lateral x-ray showing antibiotic beads in defect after resection of the talus. This patient had septic osteonecrosis of the talus requiring resection. **b** Side view of the ankle arthrodesis frame applied after removal of the beads and preparation of the tibia and calcaneus for fusion. Gradual leg shortening was done and LLD was treated by adjusting a contralateral amputation prosthesis

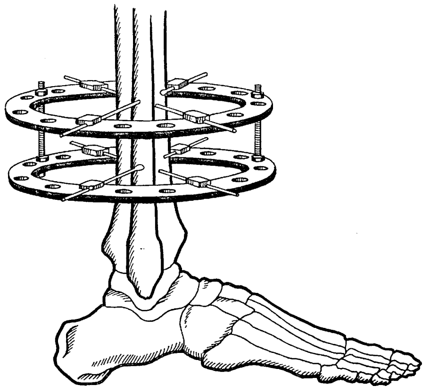

Fig. 20. Two Ilizarov rings used as a tibial base for many ankle corrections

compression across the ankle is used for arthrodesis. A proximal tibia ring is for proximal tibia lengthening or deformity correction.

Ilizarov frame considerations

The frame should be applied to the leg so that rings are perpendicular to the bone axis, the rods are parallel to the bone axis, and there is adequate clearance between the soft tissues and the rings especially at the posterior leg. The bone defect edges should be perfectly pointed toward each other to avoid deformity and to optimize contact at the anticipated docking site. If deformity should occur, this can be managed with frame modification and/or a surgical procedure to optimize contact at the docking site.

Taylor Spatial Frame considerations

Rings are placed on either side of the defect site and the anticipated lengthening site(s). The rings can be placed independently to optimally fit the leg. This is called the *rings-first method*. One ring is chosen as the *reference ring* for each level of movement, and it is important that this ring be placed orthogonal to the axis of the tibia. Mounting parameters are defined by the center of the reference ring and this will define the point in space where the deformity correction will occur. It is important to maintain enough distance between rings so that the struts can fit properly. In this frame, one is limited by the shortest length of strut. The advantages of this frame are that the application is easier and the fit on the leg is better when using the rings-first method. Also, residual deformity at the lengthening and docking sites can be addressed by using the same frame to correct angulation and translation simultaneously in the coronal, sagittal, and axial planes without major frame modification. This allows precise docking with optimal bone contact and minimizes angular deformity at the docking and lengthening sites [16].

Ankle distraction

The frame includes a proximal circular ring placed about 8 cm above the ankle joint, a foot ring, and hinges at the ankle joint.

The proximal ring is positioned perpendicular to the axis of the tibial shaft. A temporary smooth K-wire is inserted through the talus from the center of the tip of the fibula and then directed to the center of the tip of the medial malleolus in a proximal and anterior direction. This is then checked under the fluoroscope to ensure proper placement. This is perhaps the most crucial portion of the procedure because it marks the true oblique axis of the ankle joint. This wire will mark the hinge position to allow the talus to move smoothly within the mortise as it is distracted.

A foot ring is then secured to the hind foot and midfoot by placing 2 smooth wires in an oblique fashion through the calcaneus and cuneiforms/cuboid, respectively. These are then tensioned and secured as described above. The foot ring is positioned parallel to the plantar surface of the foot. A transverse midfoot wire is inserted and tensioned to the ring.

Using the previously placed guide wire for the true axis of the ankle joint, 2 universal hinges are secured to the foot ring attached at points defined by the temporary joint axis wire. The joint axis wire may then be removed. The hinges are then secured to the proximal ring placed on the tibia using threaded rods and short connection plates. These rods should be perpendicular to the ankle in both the coronal and sagittal planes. A compression/distraction rod is placed anteriorly to control ankle range of motion, thus completing the frame. The ankle joint is then taken through a range of motion under fluoroscopy to ensure smooth symmetric motion of the talus within the mortise. The ankle is then taken through a range of motion under fluoroscopy to check the amount of distraction as well as to double check the alignment. Gradual distraction of 1 mm/d in 4 separate daily adjustments for 1 week is prescribed. A total of 6 to 7 mm of distraction is achieved.

Supramalleolar osteotomy

The middle tibia ring block is applied. A distal tibia ring is fixed with 2 or 3 tensioned 1.8-mm wires and an anteromedial half pin (just medial to the tibialis anterior tendon). The rings are applied to match the deformity. TSF struts are used to connect the rings across the deformity. After a percutaneous osteotomy [18] of the distal tibia and the fibula, a gradual correction of the deformity follows as per the Ilizarov method. If there is an ankle contracture, then a foot ring is placed and gradual correction can be done simultaneously. Hinges are placed at the axis of the ankle as in the situation of an ankle distraction. A pulling rod can be placed anterior or a pushing rod posterior to motor the correction.

Ankle arthrodesis

The ankle is approached in an open fashion, and the joint surfaces are prepared for arthrodesis. This involves removal of remaining cartilage, fibrous tissue, and correction of deformity. Wedge excision from the tibial plafond may be needed for deformity correction. In case of an acute positioning, there should be excellent contact and alignment between the tibia and talus (or calcaneus). The position should be held with provisional wires placed from the bottom of the heel (Fig. 21a).

Compression between the middle tibia ring block and a foot ring is necessary. The foot ring is fixed to 2 oblique calcaneus wires and a midfoot wire. A forefoot wire can be added if extra stability is needed. A talus wire can be used to protect the subtalar joint from compression in the situation of a tibiotalar arthrodesis (Fig. 21b). This is not needed for to tibio-talo-cancaneal arthrodesis or a tibio-calcaneal arthrodesis (Fig. 21c). Compression across the ankle is performed with longitudinal rods in line with the mechanical axis of the leg (Fig. 21d). If there is a desire for gradual correction through the arthrodesis site, this may be done with TSF struts.

Bone transport for infected nonunions

All nonviable bone and soft tissue is debrided. Bone is debrided back to healthy-appearing bone with open IM canals and with bleeding surfaces. This is best done without the use of a tourniquet. Bone cuts are typically made perpendicular to the anatomic axis of the tibia by using a power saw cooled with saline irrigation. A K-wire placed with the help of fluoroscopy is used as a guide for the bone cut. In the adult patient, rings are applied with a combination of 1.8-mm Ilizarov wires and 6-mm hydroxy-apatite-coated half pins. Smaller-sized wires and half pins may be used in children. The 1.8-mm wire is placed perpendicular to the axis of the bone in the coronal plane. The ring is attached with about 2-finger-breadth spacing between the skin and the ring and the wire is tensioned to 130 kg. The half pin is then placed setting the ring perpendicular to the sagittal plane bone axis. A ring block is either 1 or 2 rings. Each ring block should have a combination of 3 to 4 wires and/or half-pins. In situations where there is a very short proximal or distal tibia segment, consideration should be given to extending the fixation across the knee or ankle. This strategy is most commonly

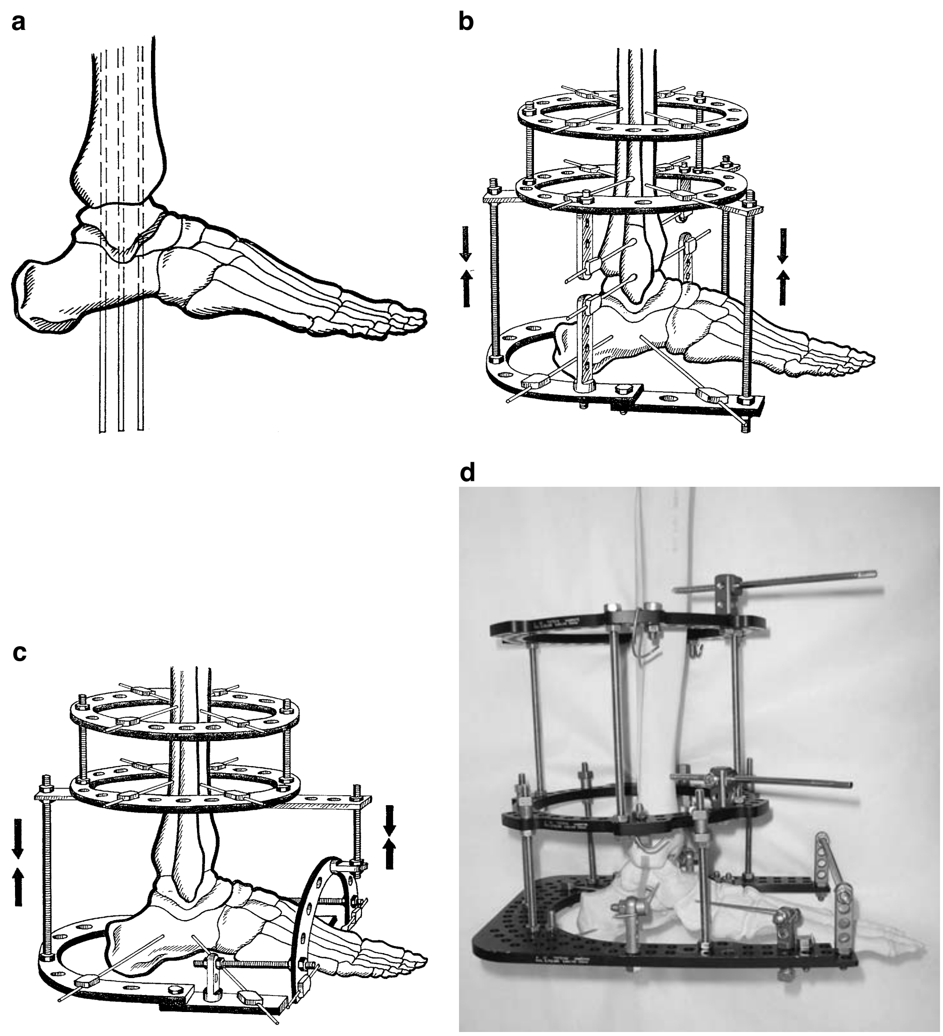

Fig. 21. **a** Provisional fixation of ankle arthrodesis with axial wires before application of the Ilizarov/Taylor Spatial Frame. **b** An ankle arthrodesis frame. Note the talus wire that serves to prevent compression of the subtalar joint. **c** Schematic diagram of an ankle and hind foot arthrodesis frame. There is axial compression from tibia to calcaneus. There is also option of compression across the talonavicular and calcaneocuboid joints. **d** Ankle arthrodesis frame mounted on saw bone

used for a short distal tibia segment with extension of the frame to the foot, at least temporarily.

With the *monofocal* approach, there is one level of activity. A ring block is applied both proximal and distal to the defect. The space between the innermost rings is chosen so that after docking there will be adequate room to approach the docking site for possible bone grafting or wound revision surgery. Ideally, this space should be greater than 5 cm. Connecting rods or struts are placed between the innermost rings to be used for compression or gradual shortening. The fibula must have a defect that is comparable to the tibial defect. A modest amount of acute shortening may be done. Pulses should be checked to make sure that this does not cause any vascular compromise. Limb shortening will occur.

With the *bifocal* approach, there are 2 segments with activity. One segment (the defect) is undergoing compression/shortening, and one segment (the bony regenerate) is undergoing distraction/lengthening. This can maintain the length of the limb. A ring block is applied on either side of the bone defect. The space between the innermost rings is chosen so that after docking there will be adequate room to approach the docking site for possible bone grafting or wound revision surgery. Connecting rods or struts are placed between the innermost rings to be used for compression or gradual shortening. Another ring block is placed on the other side of the anticipated lengthening osteotomy site. Rods or struts are applied across this segment and are set up for lengthening or distraction. The rods are then disconnected in preparation for the osteotomy. The osteotomy is done in a percutaneous fashion [48] using either the multiple drill hole and osteotome technique or the Gigli saw technique. Care is taken to perform this osteotomy outside the zone of injury in healthy bone. Ideally this osteotomy is done in the metaphyseal bone. The proximal metaphyseal location is preferable to the distal metaphysis because of increased bone regeneration potential [10].

In conclusion, the PTA has many faces. After analysis of the personality of the ankle, one can implement a rational modular treatment approach. The Ilizarov method can be used to comprehensively address the PTA with distraction, correction of bony deformity and soft tissue contracture, osteotomy, arthrodesis, and lengthening.

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