Ilizarov and trauma reconstruction

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Summary
The Ilizarov method can be used to reform missing bone and soft tissue, whether bone loss has occurred because of trauma, or if bone has to be resected because of infection or non-union. Any deformity of bone such as shortening, angulation or rotation may be addressed, often simultaneously, with correction of the deformity either in isolation or while treating non-union. The Ilizarov technique offers the opportunity to cure conditions not readily manageable by conventional internal fixation techniques. However, it does require specialist training and can be associated with its own set of problems and complications.

Introduction
The Ilizarov technique has now been used in the UK and the US for 15–20 years. It offers an effective and reliable treatment for some of the most challenging conditions in orthopaedics, such as infected non-union of long bones and malunion. The Ilizarov method uses fine wires, inserted percutaneously into bone, which are attached to a circular frame and tensioned to provide a strong stable frame construct. Gavril Ilizarov developed this method out of necessity, because of poor resources and a large population, in Kurgan in Russia. He first treated patients with this method in 1950s but only became well known in Russia after treating the Russian high jump gold medallist Valery Brummel. The athlete had sustained an open tibial fracture and subsequently developed an infected non-union that Moscow surgeons had failed to treat successfully. After treatment by the Ilizarov method Brummel returned to compete in the Olympic Games.

Basic science
Ilizarov performed a large variety of experiments from the early 1950s and developed the principle of the tension-stress effect. An osteotomy performed through bone followed by slow controlled tension applied through soft tissues stimulated increased proliferative and metabolic activity in all tissue types. Ilizarov observed that the collagen produced was orientated along the plane of stress applied through the tissues. Subsequent formation of bone regenerate then consolidated proximally and distally, furthest away from the central area of regenerate bone, which remains highly active in regenerate production.

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(intramembranous ossification). The active central area contains type 1 collagen and osteoid-producing osteoblasts. The new bone is laid down along the collagen bundles and consolidates into columns of bone lying parallel to the distraction force.

In addition to new bone formation, the tension-stress effect promotes intense angiogenesis. Capillaries form between the new columns of bone, again orientated parallel to the distraction force. This phenomenon is responsible for increased regional perfusion of the limb being treated when compared to the control limb. The increased blood flow persists for up to 4 months after the corticotomy has been performed.

Distraction also results in the growth of new muscle, fascial, nerve and skin tissues. Muscle tissues tolerate lengthening well, but increasing limb length by 30% or more produces histological changes. Nerves and blood vessels show temporary features of degeneration that will resolve after distraction is completed. The newly formed tissues were noted by Ilizarov to be similar in structure to embryonic and foetal equivalents.

Ilizarov found several factors to be important for the optimal production of new tissues. The configuration of the circular frame should provide as much stability to the fracture or osteotomised bone as possible. Excess movement between the distracted bone ends secondary to inadequate frame constructs can cause bleeding into the regenerate with resultant formation of cystic areas or cartilaginous islands, leading to non-union of the regenerate tissue. There should also be as little disturbance to the surrounding tissue.

### Table 1 Key factors in the Ilizarov method.

- Stable frame construct
- Low energy corticotomy
- Preservation of periosteum
- Preservation of marrow
- Latent period
- Low rate of distraction (0.5–1 mm daily)
- Frequency of distraction

### Table 2 Spectrum of non-unions.

<table>
<thead>
<tr>
<th>Favourable factors</th>
<th>Unfavourable factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypertrophic</td>
<td>Atrophic</td>
</tr>
<tr>
<td>Stiff</td>
<td>Mobile</td>
</tr>
<tr>
<td>Non-infected</td>
<td>Infected</td>
</tr>
<tr>
<td>Good soft tissue cover</td>
<td>Poor soft tissue</td>
</tr>
<tr>
<td>No mal-alignment</td>
<td>Deformed</td>
</tr>
<tr>
<td>Healthy host</td>
<td>Multiply operated</td>
</tr>
<tr>
<td></td>
<td>Debilitated host</td>
</tr>
</tbody>
</table>

### Table 3 Spectrum of hosts.

- Young
- Healthy
- Elderly
- Steroid treatment
- Radiotherapy
- NSAIDs
- Smoking
- Alcohol intake
- Poor nutritional status

Figure 1 Case 1: Radiographs of first intramedullary nailing of fracture. Note absence of callus.
soft tissue envelope as possible, in order to preserve the periosteal and endosteal blood supplies of the bone. Finally, the rate and frequency of distraction should be such that the tension-stress effect is maintained without causing damage to tissues by over-aggressive traction, which can result in abnormal muscle function, abnormal nerve structure and conduction. Additionally, too rapid distraction induces significant pain for the patient. From Ilizarov’s research, the optimal rate of distraction is 1 mm per day in four equal increments. Slower rates will produce premature bone consolidation, while faster rates are associated with abnormal structure of the soft tissue envelope and production of fibrous tissue at the regenerate site, i.e. the development of a fibrous non-union.

Plain radiographs allow monitoring of the distraction and consolidation phases of treatment. Numerous studies have shown that the distraction gap mineralises from the bone ends toward the central area of the regenerate bone. The central radiolucent zone should be maintained between 4 and 6 mm to avoid premature consolidation, a risk if the central gap measures 2 mm or less, or non-union if the regenerate gap is 8 mm or more. Metaphyseal sites tend to form bone and remodel quicker than diaphyseal sites, but, overall, 1 cm of limb lengthening requires an average of 3-4 months of treatment using the Ilizarov method, including distraction and consolidation phases (Table 1).

**Technique**

The basic technique involves fixation of two or more segments of bone, and an osteotomy performed percutaneously. At operation, fine wires of 1.8 mm diameter are pushed through the soft tissues to the bone surface, then driven through the bone at low speed to avoid thermal damage to the bone. If bone were burnt by excessive heat from drilling then this would promote infection of pin sites during treatment and the possibility of ring sequestra formation.

The wires are placed in such a position as to penetrate as little soft tissue as possible to avoid tethering during the corrective stage of treatment. Wires that have an olive present are used to direct the bone during treatment by effectively pushing or pulling bone segments into place. All
the wires are attached onto a circular frame that is built to correspond to the wire positions. They are secured by clamping them onto the frame with slotted and cannulated bolts. One end is secured as tightly as possible to the frame, then the opposite end tensioned before being secured onto the frame. When the appropriate site for the osteotomy is decided, a small incision is made to allow multiple drill holes to be made across the bone. Again, this is done at low speed to avoid thermal damage to the periosteal tissues. An Ilizarov osteotome is used to connect the drill holes and complete the osteotomy.

This surgery is followed by a latent period of 7–10 days to allow the bone to start healing prior to correction. Thereafter distraction of the osteotomy begins and regenerate bone is formed, the technique being termed “distraction osteogenesis”. During this phase of treatment,

Figure 4  Diagram showing the effect of hinge placement on compression, distraction and lengthening. (i) Closing wedge with compression opposite hinge. (ii) Simultaneous compression and distraction with no lengthening. (iii) Distraction on concave aspect of deformity with no increase in length. (iv) Opening wedge with distraction. (v) Increased length during correction of deformity.

Figure 5  Case 1: Radiographs showing deformity corrected and non-union converting to union.

Figure 6  Case 1: Final radiographs.
close follow-up is required with repeated radiographs to ensure the correction is proceeding as planned, and to ensure the patient understands their prescription for correction of the deformity or distraction.

There follows a consolidation phase once the new bone has been made, and using these techniques 1 cm of mature bone can be ‘regenerated’ in 40 days. By this method, segmental defects of bone can be reconstructed.12

Patient assessment

The typical patient with a non-union will probably have lost their job, and be suffering chronic pain. They are also likely to be adversely affected psychologically, many describing depressive symptoms and occasionally marital discord or even divorce. They may have had two to three unsuccessful operations in an attempt to get their fracture to heal before they present at a tertiary

Figure 7  Case 2: Mobile non-union (pseudarthrosis).
reconstruction clinic. Some delayed unions or non-unions are easier to deal with than others and, like the fractures that produced them, they can have different personalities (see Tables 2 and 3).

Non-unions are often classified into hypertrophic and atrophic morphology. Ilizarov classified non-unions as stiff or mobile. Stiff correlates with a hypertrophic non-union that has fibrous tissue present, mobile indicates an atrophic non-union with very little fibrous tissue present. The hypertrophic non-unions can be stimulated to form bone by altering the mechanical environment, either by distracting the non-union or compressing it. Atrophic non-unions tend to need surgery at the non-union site to promote biological activity, and radical debridement of dead bone, particularly in the infected cases, is required. We present a series of cases treated in our unit to illustrate the techniques most frequently employed when using the Ilizarov method for reconstruction following trauma.

### Techniques

#### Case 1: Hypertrophic non-union

This case illustrates how the Ilizarov technique can be used to treat a hypertrophic tibial shaft non-union. This 25 year old patient injured his leg playing football, sustaining a mid-shaft tibial fracture. The initial treatment was with an intramedullary nail (Fig. 1) performed at another institution, but the fracture site was opened at the time due to difficulties passing the guide wire. The initial nail was exchanged at 3 months, but infection was present necessitating nail removal and intramedullary reaming. The fracture at this point had not healed, and the patient was put in a cast brace (Fig. 2), which resulted in tibial angulation.

He presented to the reconstruction clinic with shortening and a hypertrophic non-union with a varus deformity in the tibia (Fig. 3). Erythrocyte sedimentation rate and C-reactive protein blood tests were near normal on presentation. Biopsies were taken from the fracture site for culture and sensitivity, although at the time of frame application infection was not clinically apparent.

The position of hinges on the Ilizarov frame can be used to produce a variety of effects on the position of the limb (Fig. 4). In this case, the patient’s tibia had a varus position as a result of the non-union. Placing a hinge directly over the site of the non-union would compress the convex aspect of the deformity while distracting the concave aspect. Overall there is no increase in limb length. By placing the hinge at the apex of the convexity, an effective opening wedge is created, distraction of the non-union occurs in the concave aspect of the varus deformity. This allows correction of the deformity with the stimulus of distraction promoting conversion of the fibrous tissue in the non-union into mature bone with good reconstruction of alignment (Figs. 5 and 6). It is possible to increase limb length and correct deformity simultaneously by placing the hinge at a distance away from the apex of the concavity. As deformity correction proceeds, there is distraction across the whole of the non-union or corticotomy site resulting in limb lengthening.

#### Case 2: Atrophic non-union with true pseudarthrosis

This 45 year old patient sustained multiple injuries in a road traffic accident, including femoral, pelvic and upper limb injuries. Despite several operations for non-union (Fig. 7i–iii) of the left humerus, complicated by infection, the patient was left with a useless arm. The shoulder and elbow (Fig. 8i–iii) were stiff because of movement occurring at the non-union. Abnormal movement at the atrophic non-union site would make plate fixation fail before union occurred. At operation a true pseudarthrosis with a false capsule was seen, requiring extensive debridement before the bone ends were approximated in the Ilizarov frame (Fig. 9). The basic surgical principle of debridement of infected or dead soft tissue and bone has been applied. The Ilizarov apparatus in this case was used to provide a stable mechanical environment for the fracture and to enable the healthy bone ends...
Figure 9  Case 2: Humeral non-union compressed in an Ilizarov frame.

Figure 10  Case 2: Function of upper limb with Ilizarov frame in situ.

Figure 11  Case 2: Final radiographs showing humeral union.
to be compressed and allow the bone to heal. The excision of bone in this case did alter the overall length of the limb, but not enough to cause functional or cosmetic difficulties for the patient.

The patient described immediate benefit from the frame. He had stability with useful function in the limb compared to the flail limb at initial presentation. The stability of the frame allowed intensive physiotherapy to mobilise the shoulder and elbow. (Fig. 10). In this case, debridement and freshening the bone ends followed by strong compression in the Ilizarov frame was sufficient to obtain union of the humerus (Fig. 11).

Alternatively, this non-union could have been plated, but plaster protection of the fixation would be essential to avoid fixation failure. The physiotherapy regimen would also be delayed and there would be no facility to stimulate union by increasing compression over the course of the treatment.

Case 3: Infected non-union

This case illustrates the Ilizarov technique when dealing with an infected non-union of the tibia. The 36 year old patient was involved in an RTA with multiple injuries, including an open fracture of the distal tibia. This was initially treated with wound debridement and nailing. Six weeks following nailing, an abscess appeared over the distal tibia, which was debrided, washed out and treated with antibiotics. Further episodes of infection occurred necessitating an exchange nailing procedure, performed 6 months following the fracture (Fig. 12).

At this time, the question of amputation was discussed and the patient referred for an opinion to the reconstruction clinic. Clinically, the limb was hot, swollen and the patient’s sleep pattern was disturbed because of pain. The patient was advised that treatment in the Ilizarov frame would take between 8 and 12 months, depending on the amount of non-viable bone that would require resection and thus regeneration at a different site.

This case required bifocal treatment of the infected non-union. At operation, thorough debridement of the non-union site was performed, 5 cm of infected bone were resected and the healthy, bleeding bone ends were approximated and compressed by two distal rings. Dead and infected bone is easily distinguished by its hard marble-like quality causing the bone to splinter when resected with bone nibblers. Dead bone does not bleed. Normal bone and callus feels less brittle on resection with nibblers, and capillary bleeding known as the "paprika sign" is seen at the interface of healthy and dead bone. It is important to remember that most resections are performed under tourniquet control and further confirmation of bleeding bone is obtained when the tourniquet is deflated.

At the same operation, a corticotomy was performed in the proximal tibia to allow lengthening (Fig. 13). The proximal site was lengthened 3/4 mm a day. The distal site meantime was healing under the influence of compression and weight bearing in the frame. The biological effect of distraction of the corticotomy, which is known to produce sustained increases in blood flow distal to the limb also contributes to the union. The regenerate

Figure 12 Case 3: Radiographs of intramedullary nailing of fracture. Note bone lysis at distal cross screws.

Figure 13 Diagram illustrating the compression distraction technique used for treating an infected non-union. (i) Infected non-union with an intramedullary nail. Note bone lysis distally. (ii) Bifocal treatment with proximal corticotomy and distal non-union debridement and compression. (iii) Distal fracture union with restoration of length by corticotomy distraction.
consolidated proximally and union of the distal site was seen (Fig. 14i and ii). The frame was removed and he was placed in plaster to protect the regenerate in the final stage of consolidation.

If the debridement necessitates the resection of more than 5–6 cm of bone then acute shortening and compression, as described above, is not possible. The technique of bone transport is then used. In this situation, limb length is maintained by the Ilizarov frame. A corticotomy is performed and a segment of remaining bone is transported into the segmental defect. New bone is created by distraction osteogenesis in the corticotomy gap. Ultimately the transported segment of bone will contact distal bone at the docking site. This area is then compressed using the Ilizarov frame to promote bone union while the regenerate bone consolidates to restore the bony integrity of the limb (Fig. 15).

**Case 4: Malunion—severe tibial varus deformity**

This 40 year patient presented with a varus tibia and medial joint line pain. He had sustained an open fracture of the proximal tibia 10 years prior to this, treated with plastic surgery and a standard external fixator. The treatment was complicated by recalcitrant pin tract infections, requiring early removal of the fixator. The fracture had not completely healed at this time and the patient developed a progressive deformity in the immature callus, and he was left with 20° of tibial angulation (Fig. 16), giving him medial
joint line pain and altering the mechanical axis of the lower limb. A frame was applied with a single ring to the proximal tibia and two rings placed distally. A percutaneous proximal corticotomy was performed (Fig. 17). The frame was left in situ for 7 days before beginning distraction. The axis of the deformity was identified and the centre of rotation and angulation (CORA) identified. The CORA is identified by the intersection of the mechanical axes of the fracture fragments. The position of the hinge at this point is then able to correct the translation and angulation of the malunion simultaneously. The hinges could be placed along the line of the rotational axis in order to produce distraction or compression as required (Figs. 18 and 19). In this case, effectively an opening wedge callotasis was performed, restoring good alignment. The patient walked with the frame fully weight bearing during treatment and noted that the medial joint line pain disappeared during the treatment as the mechanical axis was corrected (Fig. 20).

Case 5: Rotational deformity correction with Taylor Spatial Frame

This 68 year old man sustained a low energy open fracture of the tibia (Fig. 21). The injury was treated by debridement and washout, and was stabilised using a standard external fixator. It had been planned to nail the tibia on the night of presentation but because there was a technical problem with the image intensifier the definitive surgery was deferred. The patient had pre-existing chest pathology,
which precluded his early return to theatre and he continued with treatment using the external fixator. The fracture displaced and rotated in the fixator but had formed too much callus to reduce back to an anatomical position acutely.

The main deformity on application of the Taylor Spatial Frame was rotation. It is important to note the 90° rotational deformity between proximal and distal fragments. This device is capable of simultaneous three-dimensional deformity corrections. Using computer software and measuring deformity parameters from antero-posterior and lateral radiographs a schedule for reduction of the deformity is obtained which can produce very accurate reductions. The frame was removed 6 weeks after gradual reduction.

Complications of treatment using Ilizarov method

The Ilizarov method is associated with its own set of complications (Table 4) that require regular follow-up and review in order to prevent or to detect and treat early and effectively. Studies have shown that the incidence of complications reduces with experience and becomes low after a surgeon has performed 70–80 cases. Paley has weighted the adverse events during treatment into early and late problems. Most commonly, superficial pin site infections and pain related to soft tissue tension during distraction are reported. The majority of superficial pin site infections can be treated with oral antibiotics although occasionally inpatient treatment with intravenous antibiotics or wire removal is necessary. Pain associated with
distraction is usually related to soft tissue tension and a period of reduced or no distraction will allow the soft tissues to recover before further distraction continues.

Conclusions

The Ilizarov method offers the orthopaedic surgical team a powerful tool with which to undertake some of the most challenging and complex cases seen in orthopaedic trauma practise today. It offers a realistic and successful treatment option for patients whose only other options may include amputation or functional bracing of an effectively useless limb. Although treatment times for the patients are long, averaging between 8 and 12 months, cost analysis has shown that limb reconstruction using the Ilizarov method is more cost effective than amputation and its associated prosthetics costs.\textsuperscript{16}

Figure 21  Case 5: (a) Lateral view with external fixator in situ. (b) AP view with external fixator in situ. (c) AP view with Taylor Spatial Frame in situ with rotational deformity evident. (d) Lateral view with Taylor Spatial Frame in situ with deformity evident. (e) AP view with Taylor Spatial Frame in situ with rotational deformity corrected. (f) Lateral view with Taylor Spatial Frame in situ with rotational deformity corrected.
The techniques do require a period of specialist training and a degree of experience in treating these complex cases is essential. The Ilizarov method has a high success rate due to the trophic effect of distraction on bone growth. Ilizarov frames allow continual and progressive manipulation of the mechanical environment to give a predictable treatment course, with resultant bone of good quality. Furthermore, the mechanical strength of the fixators allows the removal of all metalwork to ensure the eradication of pre-existing infection. The techniques also have their unique set of complications, many of which are avoidable through the use of sound surgical technique and regular patient review in the outpatient department.

References