Recent advances in external fixation

This review explores recent advances in fixator design and use in contemporary orthopaedic practice including the management of bone loss, complex deformity and severe isolated limb injury.

INTRODUCTION

Externally applied methods to stabilise the injured limb have been in use since antiquity. In the modern era, advances in technique and technology have led to the development of the external fixator, with an expansion of potential applications. This review explores recent advances in fixator design and contemporary indications including management of bone loss, complex deformity, severe isolated limb injury and the polytraumatised patient.

In 1938 Raoul Hoffmann described a modular external fixator with the ability to reduce fractures and to make post-operative corrections to the alignment of fragments in three planes with the frame in situ.[1] This was the prototype monolateral adjustable fixator and continues in widespread use in its third incarnation.

In the period following the Second World War, Gavriil Abramovich Ilizarov developed a fine wire circular fixator for use in the management of fractures, nonunions and deformity. This device was patented in 1952 and has developed into a highly versatile apparatus which, in common with the monolateral fixator, is widely used today.

DISTRACTION OSTEOGENESIS

Ilizarov used the term "regenerate" to describe the bone formed in distraction osteogenesis and investigated the biological and mechanical factors that were fundamentally important for bone formation.[2-4] The conclusion of these canine experiments, in association with 40 years of clinical experience, was that osteogenic activity was positively correlated with increased stability of the external fixator, with unstable constructs tending to result in pseudoarthroses. De Bastiani popularised distraction osteogenesis in Europe with the Orthofix monobody external fixator and introduced the term 'callotasis'.[5] The technique involved a tissue preserving osteotomy and, after a delay, distraction at 1 mm per day. When the target length was achieved, the fixator was dynamised, allowing load sharing between fixator and bone.

Monolateral fixators are stiffer than fine wire circular fixators in axial loading,[6] particularly the bulky monobody designs.[7] They are less resistant to torsion and bending when forces are applied outside the plane of the monolateral device.[8] This produces asymmetrical (anisotropic) loading, which may be detrimental to fracture healing and osteogenesis. Increased stability can be achieved with increased diameter of fixation pin, pin placement at the periphery of each bone segment, decreasing the distance between the rods and the bone, increasing the number of connecting rods, and using multiplanar fixation.

Fine wire circular fixators, in general, produce symmetrical (isotropic) loading of regenerate or fracture. They exhibit non-linear stiffness behaviour under axial loading[8,9] with low stiffness at low loads stimulating callus formation, and increased stiffness at higher loads protecting regenerate bone from excessive strain. Stability of the construct is improved by utilising the smallest diameter rings that give adequate soft tissue clearance, avoiding excessive distance between the rings and using two rings per bone segment.

An external fixator that employs elements of both monolateral and circular fixators, is termed 'hybrid'. This describes a construct in which one bone segment is fixed to monolateral bars and another to a ring, or where rings are used for all segments, but with a combination of wires and half pins attaching bone to ring.

The use of half pins, particularly in the tibial diaphysis, allows bone-to-ring fixation without transfixion across myofascial compartments. Many centres have adopted this hybrid technique, reporting improved patient tolerance, but it is uncertain whether hybrid constructs maintain the favourable biomechanical properties of the fine wire Ilizarov fixator. In vitro studies have investigated the biomechanics of hybrid fixators[10-16] but the multiplicity of possible frame configurations and component variables make it difficult to compare results. Yang et al[14] demonstrated that replacement of one fine wire with a 6 mm half pin on each ring of a standard four-ring/eight-wire Ilizarov construct resulted in



S. Nicol FRCS(Tr & Orth), **Consultant Orthopaedic Surgeon**
South East Coast Limb Reconstruction Unit, Brighton and Sussex University Hospitals NHS Trust, UK
M. Jackson FRCS(Orth), **Consultant Orthopaedic Surgeon**
Bristol Limb Reconstruction Unit, Bristol Royal Infirmary, UK
F. Monsell PhD FRCS(Orth), **Consultant Orthopaedic Surgeon**
Bristol Limb Reconstruction Unit, Bristol Royal Infirmary and Royal Hospital for Children, UK
email: fergal.monsell@uhbristol.nhs.uk

an approximately one-third increase in axial stiffness and corresponding reduction in the inter-fragmentary displacement. The authors concluded that this hybrid construct closely resembled the mechanical environment of a monolateral fixator. Lundy et al[12] investigated the mechanical properties of four hybrid fixator configurations and demonstrated non-linear stiffness characteristics similar to a conventional Ilizarov fixator.

RECENT ADVANCES IN FIXATOR DESIGN

The Stewart-Gough hexapod fixator (described in detail on p.9 of this issue) has the potential to offer the advantages of the Ilizarov system with some key advances. Management of residual deformity with a programmable fixator is straightforward, requiring no more than revision of a printed, computer-generated correction algorithm which is given to the patient, and can also be managed through the use of a mobile phone App. This allows rapid modification to be undertaken during complex deformity correction. Modification of the fixator is confined to replacement of telescopic struts and can be conducted in an outpatient setting by an assistant without specialist training. The major advantage is therefore the ease and rapidity of use combined with greater accuracy of correction.[17]

The hexapod fixator may alter the biomechanical environment at the distraction site, and some surgeons have expressed concerns that this may be detrimental to osteogenesis. To date, there has not been a prospective randomised trial comparing the hexapod with the Ilizarov external fixator (IEF), but two small comparative studies have been published. In a retrospective case-control study of paediatric limb lengthening, Iobst[18] demonstrated significantly longer lengthening index using the Taylor Spatial Frame (TSF) compared with IEF (1.8 *vs* 1.3 months/cm, p = 0.01), concluding that the TSF was excellent for complex deformity correction but the IEF was superior for simple paediatric lengthening. Conversely, Kristiansen[19] did not demonstrate a significant difference in lengthening index after case selection for comparable lengthening distances between nine cases performed with TSF and 23 performed with IEF (2.4 vs 1.8 months/cm, respectively, p = 0.17).

Case series describing distraction osteogenesis using TSF alone[20-24] report lengthening indices ranging between 1.3 and 2.5 months/cm. Direct comparison between TSF and lengthening indices reported in the multiple published series utilising the IEF is impractical due to multiple variables including anatomy of limb segment, patient age, indication for surgery and use of pure or hybrid IEF configuration.

Despite the biomechanical differences, good clinical results continue to be reported for distraction osteogenesis using pure Ilizarov, hybrid[25,26] and simple monolateral[27,28] external fixators.

McFadyen et al[29] reported results of the first 100 consecutive cases treated with the TSF system since its introduction into our unit in 1999. The majority were applied to correct nonunion and malunion, and the tibia was most commonly involved. Union was achieved in 99 cases, and complete correction of deformity in all but seven.

Advances in monolateral fixator design have led to the introduction of devices which allow correction of complex multiplanar deformities. The original Orthofix monobody external fixator has been refined, with the introduction of swivelling and multiplanar clamps, and angulation and rotation templates to facilitate complex deformity correction.

The Multi-Axial Correction System (Biomet) is a hybrid monobody fixator which utilises a central component consisting of two perpendicular hinges. In common with the IEF, placement of the hinge directly over the axis of the deformity will result in a pure angular correction, and alternative hinge placement can be used to produce deliberate translational correction or shortening/ lengthening. Unintended deformity resulting from incorrect placement of the hinge can be corrected with angulation and translation, and the system can be used with rotating rings to correct a rotational deformity. Clarke[30] utilised this fixator to correct 58 cases of tibia vara secondary to Blount's disease, and found no significant difference in complication rates compared with the devices previously used in that centre for deformity correction.

Irrespective of the design of the fixator, loosening and infection of the components used to connect the fixator to bone is a major source of morbidity. The introduction of hydroxyapatite- (HA-) coated half pins has improved the characteristics of the bone fixator interface and by bonding to bone has increased extraction torque.[31] Prospective randomised trials have shown significantly increased extraction torques and decreased rates of loosening compared with uncoated steel or titanium pins.[32-35] One prospective randomised human trial[36] reported a 50% reduction in the rate of pin site infection with HA-coated pins (p = 0.009).

STAGED MANAGEMENT OF HIGH-ENERGY AND MULTIPLE INJURIES

The role of the external fixator in the initial management of isolated high-energy limb injury has become firmly established over the past two decades. Conventional wisdom in the 1950s dictated that operative fixation of severe fractures of the tibial plafond was impossible.[37] Subsequently, development of the principles of surgical management of intra-articular fractures by the AO group led to promising results in lower-energy injuries.[38,39] It became clear that early open reduction and internal fixation (ORIF) of the higher-energy fracture patterns through traumatised soft tissues resulted in poor outcomes[40-42] with deep infection rates as high as 30% to 50%.[43,44] This has led to the acceptance of staged management of these injuries, with initial application of an ankle-spanning external fixator and surgical stabilisation delayed by up to three weeks until recovery and an improvement in outcome,[45-47] and the management of other high-energy peri-articular fractures has evolved in a similar way.

Advances in understanding the mechanism of systemic inflammatory response in the multiply injured patient[48] resulted in the introduction of Damage Control Orthopaedics (DCO), and these polytraumatised patients are now routinely managed with simple mono-lateral external fixators providing rapid, minimally invasive temporary fracture stabilisation and avoiding the 'second hit' of more invasive surgery associated with the development of adult respiratory distress syndrome and multi-organ dysfunction in susceptible patients.[49]

ACUTE FRACTURE MANAGEMENT

In AO/OTA Type C periarticular fractures of the tibial plateau and plafond, modern adjustable external fixators can provide immediate, minimally invasive and stable fixation of the reconstructed articular block to the diaphyseal segment. It is also possible to carry out adjustments in the post-operative period, facilitating anatomical restoration of articular angles and prevention of mechanical axis deviation. In a series of 44 AO/OTA Type C fractures (30 of which were C3 fractures, 27 of those highly comminuted), union was achieved in all cases with normal coronal plane alignment in 52% and no cases of condylar angulation greater than ten degrees.[50]

In our experience, the hexapod circular fixator is effective in the management of long bone diaphyseal fractures, particularly those of the tibia, which are irreducible closed and where the soft tissues will not permit open reduction. Stable fixation can be achieved with the fracture shortened and translated, reducing the tension in the soft tissues, with gradual fracture reduction in the post-operative period and definitive fixation until union without the need for further surgical intervention. Joint mobilisation can begin immediately, but weightbearing may be difficult until satisfactory alignment of the limb is restored.

Paediatric and adolescent tibial diaphyseal fractures that are associated with a significant soft-tissue injury are frequently unsuitable for open reduction and plate fixation, and the presence of open physes precludes the use of an intramedullary device. Monolateral or conventional circular external fixators are an accepted treatment but fixator adjustment in the post-operative period may be difficult.

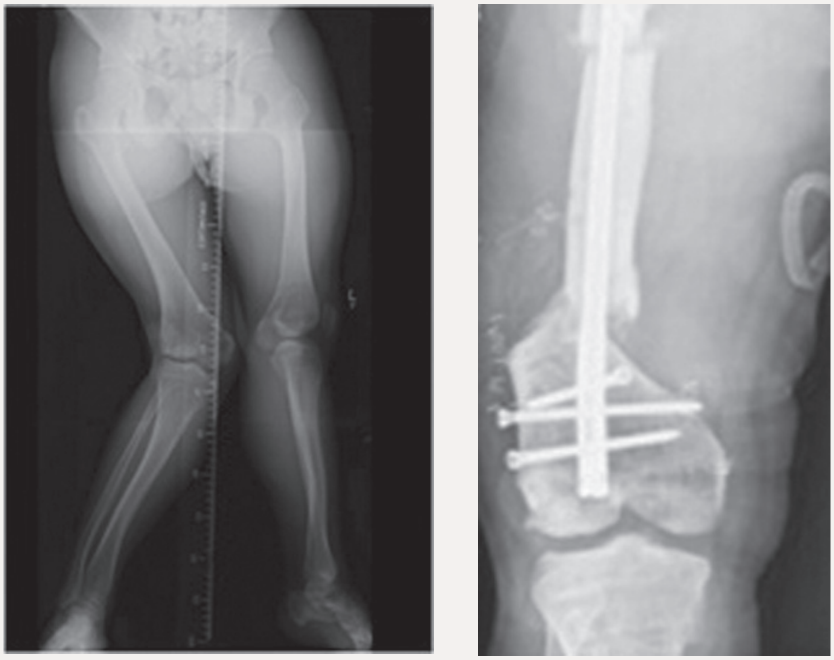

Fig. 1a, b
Computerised Hexapod Assisted Orthopaedic Surgery (CHAOS) for femoral deformity correction.

Al-Sayyad[51] reported the use of the TSF in ten unstable adolescent tibial fractures, five of which were open. All fractures united at a mean time of 18 weeks, with no significant rotational, angular or axial deformity. Eidelman[52] reported similarly excellent results using the TSF, and we reported the results of ten consecutive high-energy open diaphyseal tibial fractures in children of mean age 11 (range 5-15) which were managed with the TSF.[53] There were no cases of delayed union or nonunion, with a mean time to union and frame removal of 16 weeks, with minimal residual deformity.

COMBINING TECHNIQUES: EXTERNAL FIXATORS WITH PLATES AND NAILS

The management of patients with multi-apical deformity is complicated, especially in association with limb-length discrepancy. Patients typically require a protracted period of fixator use following lengthening to allow maturation of regenerate prior to frame removal. Lengthening in isolation[54] and in the presence of deformity[55,56] has been managed with a combined approach using circular or monolateral external fixators with intramedullary nails. In a matched-case comparison, femoral lengthening over an intramedullary nail reduced the external fixator time by almost one half ($p < 0.001$) and more than doubled the rate of recovery of knee motion, compared with lengthening with the fixator alone.[55] Kocaoglu[57] reported the results of femoral deformity correction and lengthening over an intramedullary nail using a monolateral external fixator in 28 cases, with a mean length gain of 6 cm and an external fixation index of just 0.5 months/cm.

Although a small early series using this technique in the tibia was associated with a high rate of significant complications,[58] more recently published large series support its use,[59-63] and Guo[61] reported the results of a retrospective study of tibial lengthenings using Ilizarov external fixation over a nail (51 cases) compared with Ilizarov external fixation alone (23 cases). The mean lengthening was 7.4 cm with no difference in the lengthening or consolidation index. The complication rate in the fixator over nail group was less than half of that observed with fixator alone.

COMPUTER HEXAPOD ASSISTED ORTHOPAEDIC SURGERY (CHAOS)

A technique of distal femoral deformity correction using fixator-assisted nailing has been described by Gugenheim.[63] A Hex-Fix monolateral fixator was used in 12 cases and the IEF in the remaining two cases to acutely restore normal distal femoral anatomy, prior

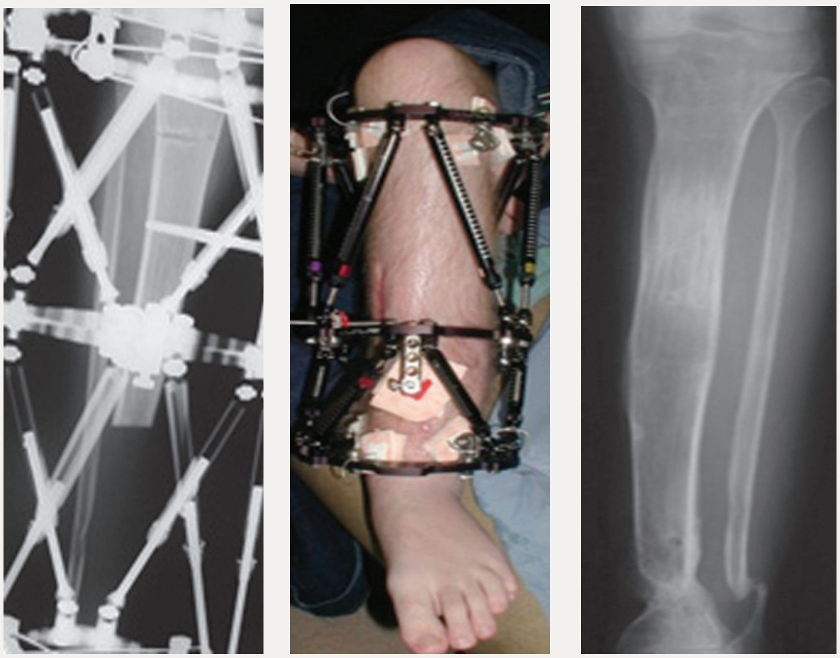

Fig. 2a, b, c Bone transport following infection.

to retrograde intramedullary nailing, with healing of the osteotomy at a mean time of 13 weeks. This technique has also been described for the management of distal femoral periprosthetic fractures[64] and windswept deformity of the knees.[65]

While these papers describe an elegant solution for these difficult cases, we have struggled to obtain sufficient stability of the distal fragment, and accuracy of reduction of complex multiplanar deformities with monolateral devices and the IEF. This has led to the development of a technique that uses the stability of a ring fixator, and accuracy of reduction provided by the TSF and has provided a straightforward solution for complex deformity.

The pin placement involves anteromedial and anterolateral half pins in a convergent configuration. This allows passage of a retrograde intramedullary nail without alteration of the fixator. The proximal ring is secured with two half pins inserted proximal to the tip of the nail. This technique is easily modified by rotating the distal ring to allow insertion of a lateral locking plate.

The accuracy of the TSF programme allows precise reorientation of the distal fragment allowing anatomical reconstruction. Our initial experience involved eight femoral deformity corrections in seven patients.[66] All deformities were complex oblique plane deformities, often with a rotational component, and ranged from ten degrees valgus to 35 degrees varus; up to 45 degrees of external rotation; 10 mm of translation and in one case, 100 mm of shortening. All patients underwent acute intra-operative deformity correction mediated by the TSF prior to definitive internal fixation using either a percutaneous locking plate or locked intramedullary nail. Deformity correction and restoration of the mechanical axis were achieved in all cases. We have subsequently expanded the use of this technique to allow multilevel femoral osteotomy correction of multiapical deformity (Fig. 1).

BONE TRANSPORT

Bone transport is a technique in which a segment of bone is gradually moved from the site of an osteotomy to the end of a segmental defect, usually under the control of an external fixator. Bone forms in the gap by distraction osteogenesis and the technique can predictably bridge skeletal defects between 5 cm and 10 cm.

The technique has been described for the management of acute high-energy open fractures with bone loss,[68] chronic post-traumatic intercalary defects,[69, 70] atrophic and infected nonunions,[71-73] and for reconstruction after excision of benign and malignant bone tumours.[73,74] The technique can be performed using a monolateral or circular fixator and relies on stable fixation and precise alignment of the donor and recipient bone segments. This may present major technical difficulties in long segmental transport, where, by definition, the segment will transport in a straight line, but due to the natural bowing of the femur and, to a lesser extent, the tibia, the transporting segment fails to dock. Repeated reorientation of the fixator, and occasionally an open procedure to realign the segments, may be necessary. This can be avoided if very accurate application of the initial IEF can be achieved, but the use of a hexapod circular fixator facilitates ongoing correction of alignment during the transport without fixator reconfiguration. The fixator is constructed using a three-ring system, one pair lengthening, and the second shortening to allow gradual displacement of the transporting segment. Fixation of this segment with half pins provides stability and prevents the 'yawing' that is associated with a fine wire construct, which can result in shearing of the regenerate, delayed bone formation and an extended treatment time. Residual programming permits very accurate apposition of the bone segments and obviates the need for an open docking procedure in the majority of cases (Fig. 2).

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CONCLUSION

External fixation devices have been in use for over 2000 years, but in their modern incarnation have become extremely versatile. Traditionally regarded as devices for the temporary stabilisation of fractures prior to definitive fixation, the experimental and clinical work of Ilizarov and his successors has resulted in a significant expansion of the indications. External fixators are employed in contemporary practice in definitive management of complex trauma, correction of complex deformity and limb salvage by bone transport. The hexapod ring fixator has built upon the strengths of the original IEF, increasing its versatility and ease of use in these complex cases.

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