Review Article

Distraction Osteogenesis: A Review of the Literature

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Abstract

Distraction osteogenesis has been one of the most remarkable achievements in musculoskeletal surgery. It is the sheet anchor for the process of limb lengthening and internal bone transport as well as gradual deformity correction. It has revolutionised the management of limb deficiencies and bone loss. Since its conception over a 100 years ago, it has gone through several stages of evolution brought on by an increasing understanding of the underlying principles that govern the successful application of the concept as well as technological advancements in the field of limb reconstruction surgery. The result of this has been a significantly changing outlook for many musculoskeletal conditions. This review looks at the historical perspectives of this concept, noting the contributions of the pioneers in this field of surgery. Its evolution and the principles governing the various aspects of distraction osteogenesis are discussed in detail. The various methods in use today and its application in modern-day orthopaedics are also critically reviewed.

Keywords: Distraction osteogenesis, internal bone transport, limb lengthening

Introduction

The origin of the term 'distraction osteogenesis' is credited to Gavril Ilizarov.[1] It describes the process of inducing bone formation between two vascularised bone fragments which are slowly and gradually pulled apart.[2] It utilises the principles of tension-stress, which determines that under gradual tension forces, living tissue responds by biosynthetic and proliferative pathway activation. Under stable conditions in this situation, new bone formation occurs by intramembranous ossification.[3]

Two broad concepts utilise this principle. The first is limb lengthening which entails an increase in the overall length of a bone, facilitated by a strategically located corticotomy or low energy osteotomy and purposed for the equalisation of length, usually and typically in a paired bone which is shortened by disease (congenital or acquired) or for the purpose of cosmesis and better aesthetics. The second is bone transport, where a segment of bone is gradually moved across a bone defect, laying down regenerate bone in its wake with the purpose of obliterating the defect. These two concepts can and have been used singly or in combination as dictated by the circumstances prevalent in the diseased limb.

The principles of distraction osteogenesis have rapidly evolved over the past 50 years, and this has revolutionised the treatment of musculoskeletal conditions to the effect that salvage and reconstruction are now possible in conditions where ablation was previously the only workable option. Conditions such as congenital limb deficiencies as well as bone loss from trauma, infection and neoplasia are now amenable to reconstitution of the resultant bone deficit. It is also now possible to correct deformities of the musculoskeletal system as well as achieve cosmetic lengthening in congenitally short individuals.

Historical Perspectives

Although controversial at the time, Alessandro Codivilla is credited with carrying out the first successful lengthening of a deformed bone in 1904, utilising skeletal traction to acutely attain his objective.[4-6] Ombredanne is credited with being the first person to use an external fixator to achieve limb lengthening in 1913.[1] In 1921, Putti introduced the concept of gradual and sustained traction rather than the acute nature in which Codivilla had taught, following his observations that

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DOI: 10.4103/njot.njot_2_20

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How to cite this article: Bafor A. Distraction osteogenesis: A review of the literature. Niger J Orthop Trauma 2020;19:1-9.

Submission: 17.01.2020 **Revision:** 30.01.2020
Acceptance: 05.02.2020 **Web Publication:** 23.07.2020

soft-tissue resistance contributed to the forces which naturally needed to be overcome to achieve lengthening.[7] This was more desirable as there had been reports of complications such as gangrene of the toes, pressure ulceration and even shock following acute lengthening. Over the next few decades, advances continued to be made both in the design and technique of limb lengthening, the most popular of which was the Wagner external fixator designed by Wagner.[8,9] The Wagner external fixator was revolutionary in the sense that it allowed ambulation as well as being versatile. Wagner's original technique described a more aggressive approach to surgery which entailed rapid distraction followed by application of a specially designed plate and bone grafting. Naturally, complication rates were high, including non-union, with other methods demonstrating superiority over the Wagner technique.[10]

The 'birth' of the Ilizarov frame marks perhaps what many deformity correction and limb reconstruction surgeons would consider the major turning point in the history of limb reconstruction and deformity correction. Gavril Ilizarov practiced orthopaedics (even though he was not a trained orthopaedic surgeon) in Kurgan Siberia, in the former Union of Soviet Socialist Republic. Consequent from the events of the second world war, his practice included patients who presented with a lot of musculoskeletal problems such as deformities, bone defects and non-unions.[11] He developed a modular external fixation construct which consisted of rings to which trans-osseous wires were attached under appropriate tension. This provided a stable fixation on which he could induce local bone formation as he gradually pulled the bone fragments apart following a minimally invasive osteoplasty (which he called a 'compactotomy'). The spread of the Ilizarov technique first to Italy and then eventually to the rest of the western world was one of the fortunate fallouts of the RA and Tigris expeditions which were conceptions of Thor Heyerdahl, a Norwegian anthropologist. Indeed, a discourse on the history of the spread of the Ilizarov technique will be incomplete without a narration of these anthropological events. On the two RA expeditions and the Tigris expedition, Heyerdahl assembled a crew of seven men amongst whom were Yuri Senkevitch, a Russian medical doctor and Carlo Mauri, an Italian photojournalist. Carlo Mauri, during the expeditions, had what appears to have been an infected malunited tibia fracture which had proven difficult to manage up till that time. Carlo Mauri, on the suggestion from Yuri Senkevitch, went to Ilizarov's clinic in Kurgan to have his leg treated as a final option (he had been offered an amputation in Italy). Following successful treatment, Carlo Mauri returned to Italy and at his prompting, Ilizarov was invited by a group of orthopaedic surgeons to speak at a conference in June of 1981 in Bellagio Italy. Thereafter, a demonstration of his amazing technique was arranged in Lecco, Italy. Following this, surgeons from Lecco travelled to Kurgan to spend time learning his techniques and soon news of this technique spread to the West (Personal communication with John Birch, June 2018) [Figure 1].

Figure 1: From left, Dr. Jessica Rivera (American orthopaedic surgeon), Dr John Birch (American Orthopaedic Surgeon), the Author and Dr. Katrin Zakharyan (Russian paediatric orthopaedic surgeon) following a history session on the Ilizarov technique during the Limb Lengthening and Reconstruction Society travelling fellowship at the Texas Scottish Rite Hospital, USA. June 2018

The Evolution of Distraction Osteogenesis

Distraction osteogenesis historically and perhaps some might say traditionally was indicated for the management of limb length discrepancy, but its principles have also found applicability in the management of limb segment deficiency through the use of bone transport techniques as well as deformity correction. Its uses have also gradually been extended to include management of craniofacial hypoplasia[12] and indeed Ilizarov's apparatus has been shown to have applicability almost anywhere on the human body as exemplified by the picture of the 'Ilizarov man' [Figure 2].

The initial apparatuses used to achieve this were external fixators, and these were a significant improvement from the acute distraction techniques, brought on by use of skeletal traction devices. Many of the early external fixator constructs were monolateral and bed-based as exemplied by the early designs of Putti, Abbott and others.[6] An improvement in technique and design of devices was driven largely by the relatively high complication rates noted with this procedure. Acute lengthening often resulted in wound breakdown, skin necrosis and non-union. Wagner introduced his external fixation device in the 70s. His technique involved incising the periosteum circumferentially with soft-tissue resection and an acute intraoperative distraction of 1–2 cm. Not unexpectedly, complication rates were high.[13] De Bastiani *et al*. improved on the external fixator designs and revised the techniques for limb lengthening surgery following observations of the high complication rates with the Wagner fixator and method. They advocated using a small incision for the osteotomy, preservation of the periosteum and a low-energy osteotomy achieved by making multiple drill holes through the cortex of the bone.

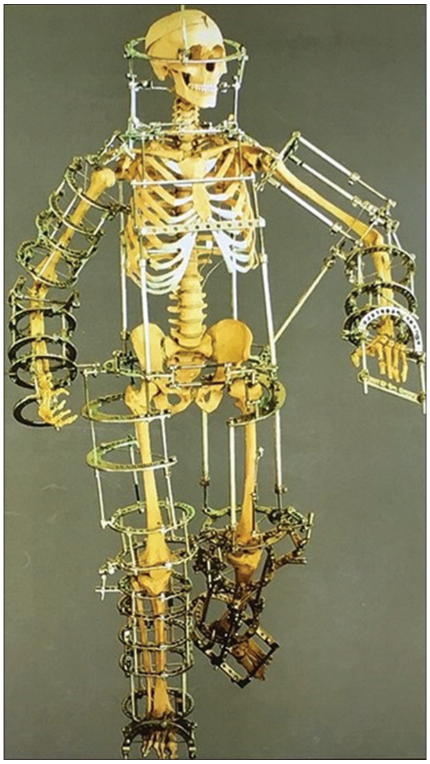

Figure 2: The 'Ilizarov man'

The ring fixator system best exemplified by the Ilizarov device represents perhaps one of the most important milestones in limb reconstruction surgery. It has shown great versatility, being able to be adapted to almost any deformity. Since then, several other ring fixator systems have been developed. The Taylor spatial frame (TSF) is one of the most widely recognised hexapod constructs used in modern-day limb reconstruction surgery [Figure 3]. Modelled after the Gough–Stewart (six-axis) platform[14] and based on a computer software programme, it has proven extremely useful in the management of complex and multi-planar deformities of the extremities.

While external fixator constructs have proven useful and versatile in their effectiveness in limb reconstruction surgery, their use has been noted to have peculiar complications. Overcoming some of these complications, most notably pin tract infection, led to the development of the intramedullary lengthening nails such as the PRECICE® nail (Ellipse Technologies, Irvine, CA, USA) [Figure 4]. Asides from the obvious and attractive option of not having to deal with pin site issues with these devices, rehabilitation is much easier and patients, not having to carry bulky external fixator constructs about, are more comfortable and less prone to accidents. Since then, improvements in design have led to an assortment of intramedullary lengthening nails as well as a relegation of the use of the external fixator frames to the correction of the more complex limb deformity cases. As opined by one expert, the birth of the intramedullary lengthening nail may just have signaled the death knell for the ring fixator in limb length equalisation

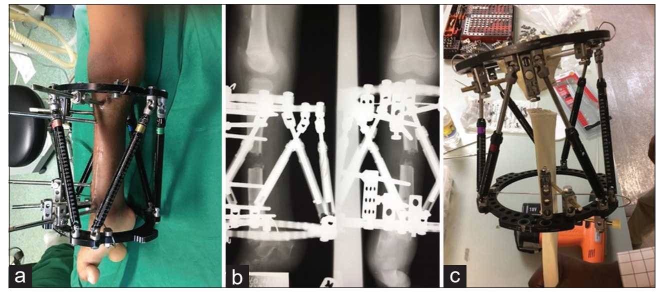

Figure 3: (a and b) Clinical and radiological images of a Taylor spatial frame mounted for pure lengthening of the tibia. (c) Taylor spatial frame mounted on a varus deformity sawbone model following correction

surgery! (Personal communication with Christopher Iobst, November 2019).

Regardless of the devices and advancements being made in limb reconstruction surgery, the basic principles of distraction osteogenesis remain a low-energy osteotomy, stable fixation, gradual distraction and bone formation by intramembranous ossification.

Corticotomy

Bone lengthening or skeletal deformity correction would be impossible without some form of osteoplasty. Several different methods have been employed including the use of motorised saws, Gigli saws, osteotomes and corticotomes. Abbott and Magnuson employed the use of a step-cut osteotomy for bone section while Ombredanne utilised an oblique osteotomy.[8,15,16] While these may appear to create a greater surface area for healing, it was only possible to achieve these bone cuts through open surgery. Furthermore, at the time, acute or rapid distraction was the protocol in vogue and fractures were not uncommon in these situations. De Bastiani *et al*. pointed out the need for a gentler method of performing the osteotomy following observations of the high complication rates noted with the Wagner technique which they had previously employed.[13] They coined the term 'Callotasis' to describe their procedure for 'lengthening by the distraction of the corticotomy callus'. In their approach, they sought to preserve the posterior periosteum and the marrow of the bone being sectioned. They achieved this by limiting the venting drill bit to project no more than 1 cm beyond the tip of the drill guide within which it was contained. This prevented the drill bit from penetrating bone far beyond the intended cortex and into the marrow, thus limiting damage to the marrow. With their technique, they achieved a reduction in complication rates from 26% (using the Wagner technique) to 14%. Interestingly, Wagner had reported a 44.8% complication rate using his own technique in femur lengthening.[9] Currently, most surgeons employ the use of a transverse bone cut, better still if done percutaneously.

In contrast to the method of callotasis as described by De Bastiani *et al*., Ilizarov emphasised preservation of the blood supply within the marrow, achieved by dividing

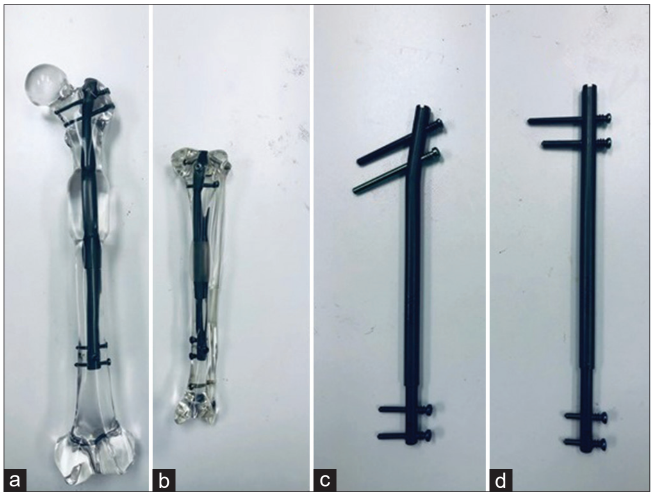

Figure 4: PRECICE nail models. (a and c) Femoral PRECICE nails. (b and d) Tibial PRECICE nails

only the cortex of the bone (corticotomy). The difference between callotasis and corticotomy lies in the prominence given to the blood supply to the bone. Whereas callotasis emphasises preservation of the periosteal blood supply and gradual distraction of the resultant callus formed, corticotomy emphasises the preservation of the endosteal blood supply.[17]

The emphasis in the osteoplasty technique is in maintaining the viability of the sectioned ends of bone and disrupting the blood supply as minimally as possible. Performing this using a motorised saw expectedly causes thermal damage and slower healing while a low energy technique minimises damage to the bone ends and thus promotes better healing. The key is to preserve the periosteal blood supply above all else as this has been shown by many authors to be the dominant contributor to osteogenesis during the distraction phase.[2,18-21]

The choice of location of the osteoplasty is also of key importance in distraction osteogenesis. Most authors agree that a metaphyseal location is the best site for an osteoplasty. The reason for this is that the metaphysis has better blood flow and a thinner cortex which makes osteoplasty here not only easier but less prone to vascular insufficiency. Diaphyseal osteoplasty is also possible, but it is advised that care should be taken to preserve the periosteum in this site to provide the best chance for healing.

Latency Period

The latency period represents the time duration between performing the corticotomy and the commencement of distraction. The basis for this is to allow the initial processes of callus formation commence following which the new callus is gradually stretched out. It has been shown to promote the formation of good regenerate bone by several authors.[19,22,23] The concept of a latency period was first introduced in 1927 by Abbott and Saunders.[8] He emphasised preservation of the periosteum and a delay in the initiation of distraction for 7–10 days. Currently, latency periods range from 5 to 10 days. Longer latency periods are indicated in situations where callus formation is expected to be slower (diaphyseal bone, older patients and situations where preservation of blood supply may have been inadvertently compromised). Too long a latency period however can lead to premature consolidation at the corticotomy site, and failure to achieve distraction while too short a period may result in tardy regenerate bone and non-union.

Distraction Rate

The ideal rate for distraction should allow for the attainment of timely and precise treatment without complications while ensuring that the best possible regenerate bone is formed which will go on to consolidation and remodelling in such a manner that the resultant bone will be expected to withstand normal physiologic loads without the need for external support. This means that it should not be too slow, neither should it be too rapid.

Ombredanne reportedly lengthened a femur at a rate of 5 mm/day, but his results were disappointing with a high incidence of infection and skin necrosis being reported.[16] Putti employed a slower distraction rate of 2–3 mm/day while Wagner distracted his patients at a rate of 2 mm/day. Ilizarov traditionally used a rate of 1 mm/day.[24] The choice of distraction rate is dependent on factors such as the age of the patient, the bone being distracted, the site of the corticotomy and the type of hardware being used (external fixator or intramedullary nail). Metaphyseal distraction generally accommodates more rapid distraction rates in comparison to diaphyseal sites. Children generally also form bone more rapidly than adults and so can tolerate faster distraction rates. Other considerations for distraction rate include the soft-tissue issues (muscles and nerves) and the adjacent joints. Currently, most surgeons utilise rates ranging from 0.5 to 1 mm/day depending on a combination of a multitude of factors. Some have advocated that in the tibia when using intramedullary nails, the distraction rate should not exceed 0.75 mm/day.[25]

There are different prescribed rhythms for distraction osteogenesis which range from a single daily adjustment to up to 60 adjustments a day in some experimental models.[24] Clinically, rhythms of daily, twice daily, three times daily and four times daily have been employed.[26] The smaller incremental rhythms are less painful for patients and appear to favour a better quality of regenerate bone formation, but the time-consuming nature of this protocol is a major drawback.

The important message is that during the distraction, close monitoring is key. Rate and rhythm should be adjusted based on the nature of the regenerate bone being formed. The goal should be to have a healthy column of regenerate bone which will go on to heal and remodel into the normal bone.

Docking Site Issues

Achieving union at the point of contact between the leading edge of the transported segment of bone and the host bone, the so-called docking site, is an important aspect of bone transport. This can be facilitated by bone grafting or injection of bone morphogenic protein at the docking site. Other issues include maintaining satisfactory alignment of the bone segments and avoiding angulation of the regenerate bone. Alignment of fragments during lengthening or transport can be ensured by careful attention to the orientation of the fixation device. Malalignment using a monolateral fixator is more likely to occur if the connecting rod or rail is not parallel to the bone when applied. Similarly, if a ring fixator is used for lengthening, malalignment is more likely if the longitudinal axis of the frame is not parallel to the longitudinal axis of the bone being lengthened. These concerns are more easily addressed if the frame set up can accommodate deformity correction. Another technique for preventing malalignment during transport with an external fixator device is to have this done over an intramedullary nail. The nail serves as a guide to the transporting segment of bone, ensuring that it is directed to the docking site.[27,28]

Consolidation Rate of Regenerate

Following successful lengthening or transport, the new bone thus formed is expected to undergo changes which ensure that it matures into a structurally sound column of bone that can withstand normal physiologic loading. Confirmation of satisfactory consolidation is a radiological process, and the duration for this process is dependent on many factors, including the age of the patient, the location of the corticotomy as well as the length of the regenerate.

The origin of the term 'Healing index' is credited to De Bastiani and colleagues[6] It is derived by dividing the total duration spent in a fixator (in days) by the amount of lengthening achieved (in centimetres). They reported a healing index of 38 days in their series. Others have used the term 'Distraction-Consolidation Index' which is derived by dividing the distraction-consolidation time ('defined as the interval in months from the date of the corticotomy until the distraction gap was healed according to radiographic and manual testing criteria') by the distraction gap (in centimetres).[29] Consolidation is greatly enhanced by early dynamisation which is facilitated by the institution of physiologic loading of the bone.

External Fixation

External fixation devices were the first forms of hardware used for distraction osteogenesis. Two main constructs are available, the monolateral fixators and the circular or ring fixators. The monolateral fixators consist of a series of half pins inserted percutaneously into bone and secured to an external bar, rod or rail system by means of purpose-designed connectors. Modifications in design have led to their use in limb lengthening and bone transport. Common examples in use today include the linear rail system and the orthofix fixator system [Figure 5]. The ring or circular fixators are the more versatile devices. They have found use not only in limb lengthening and bone transport but also in the management of complex limb deformities and even in the management of hip conditions [Figure 6]. The most popular of these is the Ilizarov fixator system. Other systems in use include the TSF, the TL-hex fixator system, OrthoSUV, Vilex, to mention but a few [Figure 7]. One of the major drawbacks of using external fixation devices is the unfortunate incidence of pin tract issues. Several protocols for pin tract care have been devised to reduce the incidence with varying levels of efficacy.[30,31] Some others have also sought to reduce the time spent in a frame by performing multi-level osteotomies in the same bone for simultaneous lengthening [Figure 8].

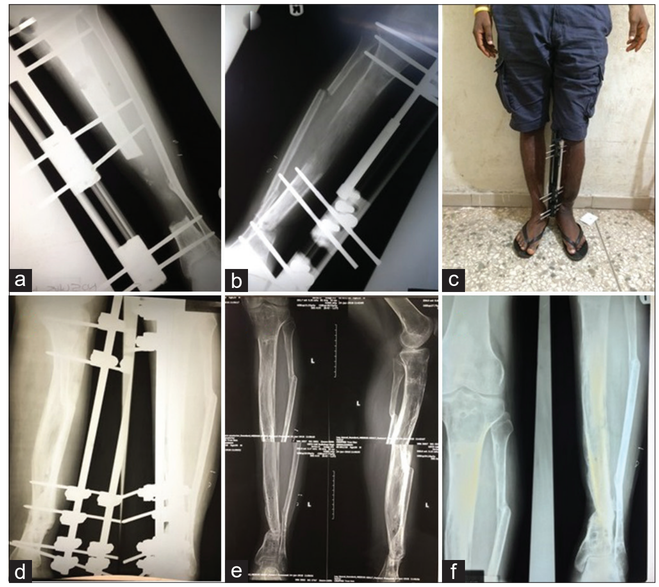

Figure 5: Segmental bone transport with the linear rail system. (a) Initial transport following segmental resection. (b) Docking completed. (c) Clinical image demonstrating full weight-bearing during the consolidation phase. (d) Consolidation of regenerate bone. (e) Following removal of the external fixator. (f) Ongoing remodeling

Intramedullary Limb Lengthening

Over the last decade, the popularity of the motorised intramedullary nail for use in the lengthening of long bones has increased, due largely to its more convenient design and the avoidance of the necessary evils of pin tracts associated with the external fixator devices. Following initial troubles with design, application and use resulting in high complication rates[32-34] it has proven to be a reliable and accurate means for achieving satisfactory limb lengthening.[35-37] It has indeed proved to be a major milestone in the management of limb length discrepancy.

Alexander Bliskunov is credited with designing the first intramedullary lengthening nail.[36] This model was a telescopic nail which had connections to the pelvis and relied on femoral rotational movements to drive the crankshaft mechanism. Since then, improvements in design and technology have yielded the development of better, more precise implants

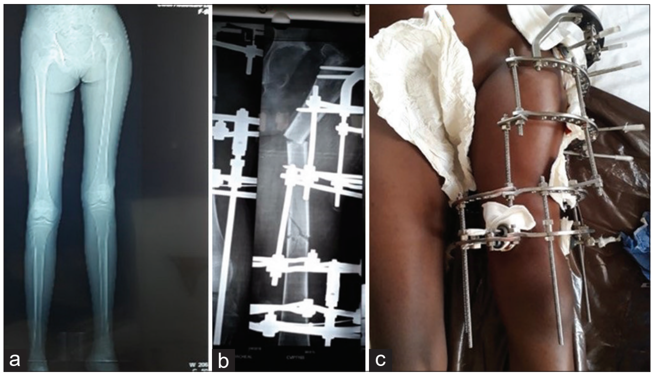

Figure 6: Ilizarov frame used for pelvic support osteotomy and lengthening. (a) Scanogram showing LLD and hip pathology. (b) X-rays showing frame assembly following pelvic support osteotomy and corticotomy for distraction. (c) Clinical image showing frame assembly. Photographs provided courtesy of Dr. Emeka Izuagba and used with permission copyright 2020, National Orthopaedic Hospital, Igbobi, Lagos, Nigeria

and instrumentation that ensure reproducible and excellent results. Examples of intramedullary lengthening nails which have been developed include the Fitbone nail (Wittenstein, Igersheim, Germany) designed and developed by Baumgart in 1991, the Albizzia nail (Depuy, Villerbuane, France) developed by Guichet and Grammont in 1994, the intramedullary Skeletal Kinetic Distractor (ISKD) (Orthofix Inc., McKinney, Texas, USA) developed by Cole in 2001 and the PRECICE nail (Ellipse Technologies, Irvine, CA) developed by Stuart Green and introduced into clinical use in the US in 2011.[36] The Fitbone nail has an external transmitter located subcutaneously and connected to the implanted nail, which lengthens when the external transmitter is activated by radiofrequency waves to drive the motor mechanism of the nail. The PRECICE nail, in contrast, has an internal gear system and drive shaft which is driven by an attached magnet which communicates with a handheld external remote control device [Figure 9].

Some of the lengthening nails had problems which necessitated their being withdrawn from the market. The ISKD was notorious for causing distraction that was in excess of the desired rate with unacceptably high complication rates, particularly non-union. Other complications with the use of the nails include hardware failure or breakage, failure to distract, premature consolidation as well as joint issues. In combating the issue of hardware failure, stainless steel alloy instead of the usual titanium alloy was used to design a newer version of the internal lengthening nail called the STRYDE nail which can support heavier loads and is thus less prone to breakage.

Soft-Tissue Considerations During Limb Lengthening

The lengthening of a bone shortened by disease is not without its effects on the surrounding and enveloping soft tissue. These issues were particularly highlighted with the use of external fixation devices. The most common among these issues were pin

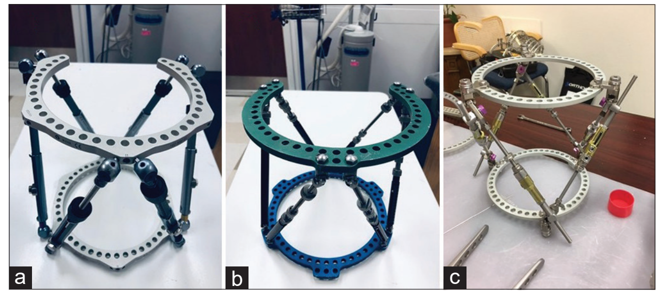

Figure 7: Ring fixator systems. (a) TL-Hex (Orthofix). (b) Taylor spatial frame (Smith and Nephew). (c) Ortho SUV frame (Ortho-SUV Ltd)

tract infections. It has also been reported that skeletal lengthening in general tends to affect adjacent muscles and nerves.[38-40]

The need to consider the enveloping soft tissue when lengthening was recognised as early as about 100 years ago by Putti.[7] He noted that soft tissue resistance was one of the issues that needed to be overcome in the course of lengthening of bones and thus emphasised the need for gradual rather than acute traction. Damage to a nerve in the cause of surgery is a potential complication. This invariably manifests in the immediate post-operative period. It is easily avoided by applying a sound knowledge of anatomy and location of the 'safe corridors' for pin placement at the time of surgery. In other scenarios, as lengthening occurs, it is possible that nerve impingement may result as the half pins or wires are transported in the course of the lengthening. Young *et al*., following observations of muscle weakness in limbs lengthened by the Ilizarov frame, carried out electromyographic and nerve conduction studies. They found abnormalities in nerve conduction studies on the deep peroneal, superficial peroneal and posterior tibial nerves in patients who had undergone tibial osteotomies for Ilizarov lengthening as well as increases in intra-compartmental pressures. They postulated that axonal type injury to the peroneal nerve may have occurred as a result of the increased intra-compartmental pressure following use of the Ilizarov frame for tibial lengthening in these group of patients.[40] Similar observations had been made by Galardi *et al*. previously.[41] Reduction in muscle strength following the removal of external fixation lengthening devices for femoral and tibial lengthening has been documented in the literature.[42] Krieg *et al*. demonstrated that lengthening with femoral intramedullary nails resulted in loss of maximum isokinetic torque of the extensor muscles.[39] They surmised that this may be the result of muscle damage and replacement with fibrous tissue and a resultant increase stiffness, muscle cells being examples of permanent cells. This theory and observations had been made by previous authors.[43,44] Muscles can tolerate up to 10% of lengthening, but beyond 30%, histopathologic changes become manifest.[45]

Complications

Complication rates following different methods for achieving distraction osteogenesis have been reported to range from as low as 5% to as high as 225%.[9,13,46,47] Perhaps positively,

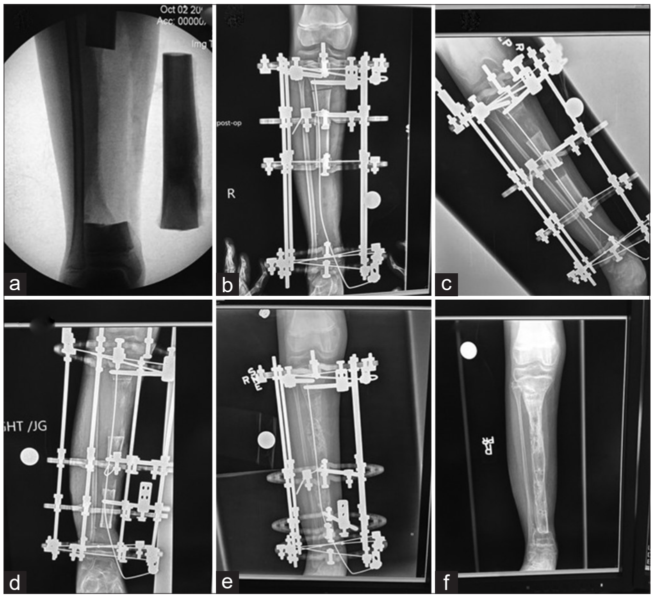

Figure 8: Multi-level bone transport to manage a segmental defect of the tibia following resection for a bone tumor. (a) Following resection of tibial bone segment. (b) Initial frame mount and first corticotomy. (c) Second corticotomy. (d) On-going distraction at two levels. (e) Docking achieved. (f) Frame removal following satisfactory consolidation of regenerate. Figures used with permission from the Rubin Institute for Advanced Orthopedics, Sinai Hospital of Baltimore, Baltimore, Maryland, USA

these rates tend to drop as experience increases.[47] It has also been the experience and belief of many that the modern internal lengthening nails have less troubling side effects when compared to the traditional fixator systems, and this has driven a shift towards an almost exclusive use of these nails for lengthening. Some of the complications experienced in the course of distraction osteogenesis have ranged from tissue damage during surgery (impalement of vessels, nerves or tendons by wires, half pins or osteotomes), infection (pin site, soft tissue and bone), malalignment, premature consolidation or fracture of regenerate, non-union, vascular insufficiency, peripheral nerve damage (acute or gradual), joint issues which include contractures, subluxation or dislocation, hardware failure as well as psychological problems.

Impalement injuries are best avoided by application of the knowledge of the 'safe corridors' for pin and wire placement. Careful attention to anatomy and surgical technique is essential. Pin tract issues are by far the most common complication affecting distraction osteogenesis achieved by external fixators.[47] Factors that predispose to pin tract issues include thermal damage from the insertion technique, inappropriately tensioned wires at the time of fixation and poor post-operative pin site care. Angulation is a potential complication with the use of monolateral fixators. This is as a result of the cantilever mechanism and consequent eccentric loading inherent in the construct. This is best attenuated by not only ensuring that the axis of the fixator matches the desired axis of lengthening but that the fixation to bone is very stable. The internal lengthening

Figure 9: Reverse planning method with a PRECICE nail for simultaneous deformity correction and lengthening. Photograph provided courtesy of Dr. Chris Iobst and used with permission copyright 2020, Centre for Limb Lengthening and Reconstruction, Nationwide Children's Hospital, Columbus, Ohio, USA

nails may also cause angulation, particularly in the femur were lengthening is carried out, necessarily, along the anatomical axis of the bone rather than the mechanical axis. The consequence of this is a lateral drift of the mechanical axis by as much as 1 mm for every 1 cm of length gained and therefore a predisposition to a valgus tibiofemoral angle.[48] Premature consolidation of regenerate bone and non-union are contrasting complications that are directly related to stiffness and stability of fixation during distraction osteogenesis. If appropriate tension is not applied to the transosseous wires, distraction rate becomes inadvertently too slow thus predisposing to premature consolidation. If the motion between the distracting fragments becomes excessive (from an unstable fixation), non-union can occur. This can occur with internal lengthening nails if there is failure of the internal mechanism in the nail or with improper technique as exemplified by the PRECICE nailing system. This system allows for compression or distraction at the osteotomy site. The direction depends on the placement of the external remote-control device. Joint contractures, subluxation and dislocation are best prevented by adequate pre-operative planning, intraoperative stabilisation of the joint (utilising either a spanning external fixator or temporary independent hardware fixation of the joint) and/or appropriate post-operative physical therapy [Figure 10]. Rarer complications such as reflex sympathetic dystrophy and compartment syndrome have also been reported.

Other Considerations

Chondrodiastasis, as a means of achieving limb lengthening, has also been described in the literature.[49,50] It refers to the concentric or symmetrical distraction of the physis. Its use is usually reserved for small limb length discrepancies of <4 cm and in patients who are within a year of fusion of the growth plate as it tends to be followed by closure of the growth plate as soon as distraction is completed.

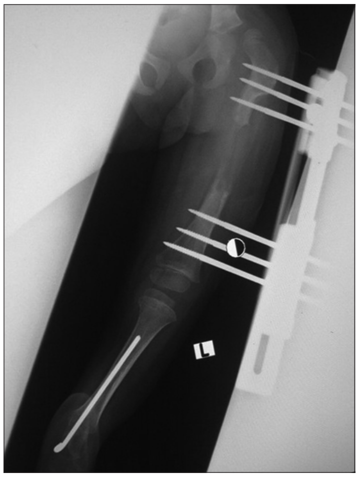

Figure 10: Hip dislocation following monolateral fixator lengthening of the femur

With improvements in design and growing experience with the use of internal lengthening nails, there has been an expansion in recent years for indications for their use. It is now possible to combine acute deformity correction and lengthening either with the use of a frame (fixator assisted nailing) or without a frame.[51,52] Some of the internal lengthening nails have also been used in an 'off label' manner as extramedullary devices in skeletally immature patients where there is a need to preserve the integrity of the growth plates[53] [Figure 11].

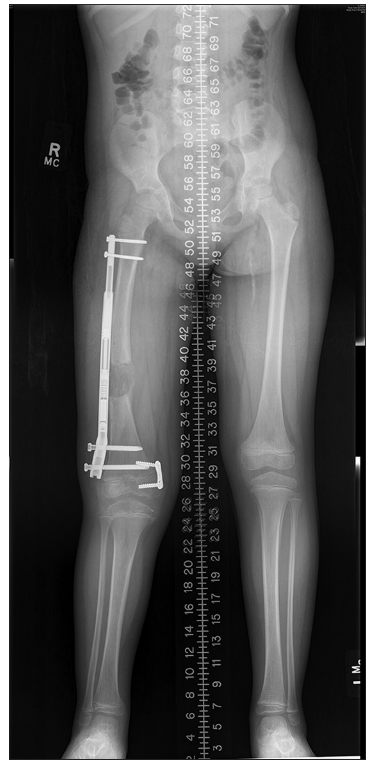

Figure 11: Femoral lengthening using an extramedullary PRECICE nail. Photograph provided courtesy of Dr. Chris Iobst and used with permission copyright 2020, Centre for Limb Lengthening and Reconstruction, Nationwide Children's Hospital, Columbus, Ohio, USA

The Future of Distraction Osteogenesis

The transport of intercalary bone segments has been possible solely with the use of external fixators. Surgeons have, however, utilised modular systems combining nails or plates with external fixation to achieve bone transport.[27,28,54,55] In these situations, the external fixator system is used for lengthening and is removed as soon as this phase of treatment is completed thus limiting complications associated with an external fixator to a significantly shorter time duration. The nail or plate continues to provide stability until consolidation of the regenerate bone is completed. Recently, NuVasive (which acquired Ellipse technologies in 2016) designed and obtained Food and Drug Administration approval for an intramedullary nail system which can support internal bone transport. Currently, studies are also on-going to design and produce bone lengthening and possibly transport plates.[56] With the introduction of these implants, external fixators would understandably have run their course in the management of limb lengthening and bone transport.

De Bastiani *et al*. introduced the concept of dynamisation in the 80s.[57] Following studies and initial promising results on the effect of 'reverse dynamisation' in animal models and the treatment of tibial fractures, there is current interest in applying this concept to distraction osteogenesis.[58,59]

Conclusion

Distraction osteogenesis has been one of the greatest revolutionary ideas in limb reconstruction surgery in the past 100 years. It has proved very versatile in its applicability in the process of achieving cosmetic lengthening, deformity correction and management of bone defects, thus making salvage possible in situations where, in time past, the only workable solution was surgical ablation. Its evolution continues to hold promise for improvement in the management of musculoskeletal conditions.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

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