Review article

Osteotomy and fracture fixation in children and teenagers

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A B S T R A C T

Significant changes have occurred recently in fixation methods following fracture or osteotomy in children and teenagers. Children have benefited the most from these advances. A child’s growth is anatomically and physiologically ensured by the growth plate and periosteum. The need to keep the periosteum intact during trauma cases has led to the introduction of flexible intramedullary nailing. We will review the basic principles of this safe, universally adopted technique, and also describe available material, length and diameter options. The problems and the limitations of this method will be discussed extensively. In orthopedics, the desire to preserve the periosteum has led to the use of locking compression plates. Because of their low profile and high stability, they allow the micromovements essential for bone union. These new methods reduce the immobilization period and allow autonomy to be regained more quickly, which is especially important in children with neurological impairment. The need to preserve the growth plate, which is well known in pediatric surgery, is reviewed with the goal of summarizing current experimental data on standard fracture and osteotomy fixation methods. Adjustable block stop wires provide better control over compression. These provide an alternate means of fixation between K-wires and screws (now cannulated) and have contributed to the development of minimally invasive surgical techniques. The aim of this lecture is to provide a rationale for the distinct technical features of pediatric surgery, while emphasizing the close relationship between the physiology of growth, bone healing and technical advances.

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1. Introduction

Many changes have occurred in pediatric osteotomy and fracture fixation over the past few years. The objective of this lecture is to discuss all these changes in the context of scientific advances in the fields of biomechanics and biology, and to highlight the most essential elements related to children and their growth. Recent data on bone healing will be reviewed first as an introduction to current options for pediatric osteotomy and fracture fixation and their biological basis. Joint fusion, common in “adult” orthopedics and spinal fixation will not be discussed here, as they comprise entire fields on their own.

2. Current data on fracture healing

There are few recent publications specific to fracture healing in children. The basis of fracture healing in children using flexible intramedullary nailing (FIN) was described in 1987 by Téot, who performed extensive experiments [1]. Biological aspects such as preserving the fracture hematoma and periosteum, the fundamental role of the periosteum and the importance of medullary vascularity were highlighted. The role of bone morphogenic proteins (BMPs), osteoblast-osteoclast interactions, contribution of ischemia and hypoxia, and electric induction phenomena were revealed. Parallels were drawn between the process of bone healing and the various stages of endochondral bone formation in the embryo. A description of the four stage of bone healing is given in Table 1 along with an overview of the growth factors and cells involved.

But biological factors are only some of the elements needed for bone healing. Bone regeneration requires three fundamental components [2]:

- progenitor cells;
- growth factors (osteoinduction);
- appropriate scaffold (osteoadhesion).

Giannoudis added the mechanical environment to this list and arrived at the diamond concept of fracture healing (Fig. 1)[3,4]. But to fully understand individual variations in bone healing, genetic variations [5], use of drugs such as NSAIDs, ageing and smoking must also be taken into consideration.

Biomedical engineering can come into play with each of these four components.
Internal fixation of mid-shaft fractures greatly evolved under the auspices of the AO Foundation. The concept of rigid anatomical fixation was transformed to a more biology-friendly design, resulting in locking compression plates [6].

The desire to maintain the mechanical environment through muscle balancing and bone vascularization led to the idea of minimally invasive surgery.

Mesenchymal stem cell-based therapies and osteoinductive factors are now being used clinically [7, 8].

Since children rarely have bone-healing deficiencies, the pediatric orthopedics world is a spectator to these developments, for now. But without true pediatric studies on bone healing, we are left to extrapolate recent scientific findings to children.

As for fracture fixation, the following points are already well known, but will be discussed in a biological context:

- keep the periosteum intact;
- do not disturb the fracture hematoma;
- flexibility is required during fixation;
- development of percutaneous surgery.

Although biomedical engineering applies only to a limited number of cases, some of the initial applications were autologous bone marrow grafting and osteopetrosis [7]. Recent applications consist of BMP treatment of congenital pseudarthrosis, bone marrow–derived mesenchymal cells in osteogenesis imperfecta [9], application of the induced membrane technique to children [10], avascular necrosis related to corticosteroid therapy, and by analogy, treatment of mucopolysaccharidoses diseases [11].

3. Role of fixation in children and teenagers

It is restating the obvious that childhood is characterized by growth and that this process is driven by two specific structures: the growth plate (or physis) and periosteum, which is a true ally for the pediatric orthopedic surgeon. Each of these structures has its own complications and problems during osteotomy and fracture fixation.

Although growth conveniently corrects many cases of malunion, it would be wrong to believe that it solves everything. Conversely, automatically reducing and fixing every fracture can also lead to problems. One must always remember that conservative (non-surgical) treatment leads to faster and more reliable healing than fracture fixation. This procedure is only indicated in current pediatric trauma practice if the fracture callus does not have sufficient remodelling capacity. The indications will mainly depend on the child’s age and the fracture site. Exceptions to this rule are poly-trauma [12], associated severe head injury, pathological fractures or certain underlying diseases such as neurological impairment or congenital bone fragility.

The following rules of remodelling underpin the indications for bone fixation:

- a malunion will be properly remodelled if:
  - the child is young (usual limit is about 8 years of age),
  - the malunion is near the metaphysis,
  - this metaphysis is highly active, with a high potential for growth (near the knee, away from the elbow, etc.),
  - the callus displacement plane corresponds to a potential movement of the neighbouring joint (high tolerance at wrist; no tolerance for valgus-varus displacement at ankle).

Any offset, or rotated callus, cannot correct itself. Be careful with supracondylar fractures at the elbow, mid-shaft fixation of the humerus and femur, and metacarpal or phalangeal fractures!

These factors help to explain the many indications for conservative treatment of wrist or proximal humerus fractures, and a large number of indications for fracture fixation at the elbow or ankle.
4. Preserve periosteum at all costs: mid-shaft fixation

For a long time, a child’s mid-shaft fracture was stabilized using “adult” hardware consisting of fairly long plates. But these plates had a plethora of complications such as scars, quasi-laparotomy of the thigh, haemorrhage and infection risks, and lengthening related to the need to remove the periosteum when implanting these large plates. Staunch advocates of this method, which is no longer used in pediatric trauma cases, believe that better control over rotation is achieved and the patient and surgeon are subjected to less irradiation. Two successive events disrupted these beliefs: the advent of FIN and the recent appearance of locking compression plates. Progress made in fluoroscopy and radiation protection was essential to overcoming the final hurdles.

4.1. Traumatology: FIN

The flexible intramedullary nailing (FIN) technique, which was developed in the 1980 by surgeons in Nancy, France, has now been perfected. This technique is also known as elastic stable intramedullary nailing (ESIN). It is now used universally since intra-operative imaging became available. This is the gold standard treatment in the English-speaking world.

FIN abides by the biological criteria described earlier. The hematoma and its growth factors are preserved. The periosteum, outside of fracture-related damage, is not destroyed. The flexibility of the construct allows for the micromovements needed to stimulate the periosteum and ensure healing. The nails do not completely fill the medullary canal, thus do not disturb the endosteal callus.

The stability of the construct is ensured in all three planes (frontal, sagittal and rotational) [13]. With the nail bent into opposite directions, three support points ensure balance and bring the construct back into balance each time a deforming load is placed on the bone. Rotational movements are controlled through medullary anchoring of the curved tips.

The technique was initially developed for femur fixation. Ender rods were the design basis for flexible nails that can be curved. It has now been applied to all long bone fractures, including those in the hand and foot. The surgical technique has already been described in detail for various indications so they will not be reviewed here [13–15]. Instead, we will emphasize a few key aspects, provide tricks of the trade, redefine the limits of technique, and outline the errors to avoid.

4.1.1. Choice of materials

FIN nails are available in either titanium or stainless steel. Both types of material have the same type of curvature and similar instrumentation [16]. Titanium is more elastic than stainless steel, which makes titanium better suited at increasing the micromovements in the construct and stimulating the periosteum. Stainless steel nails are stiffer: the stiffness of a stainless steel nail of a given diameter is the same as a titanium nail 0.5 mm larger in diameter. As a result, a larger diameter titanium nail is needed to attain the same stiffness as a stainless steel nail, but the medullary canal may not be large enough to accept it. Since both types of materials undergo similar amounts of friction-related corrosion, the choice of material is driven by the degree of stiffness desired. Roughly speaking, titanium is better for small children when a high degree of elasticity is needed. Stainless steel is indispensable in larger children and teenagers who still have open growth plates, but for whom stability is essential. The final decision comes down to biomechanics, surgeon preference and financial considerations (titanium costs more).

4.1.2. Nail size

Several methods have been described to guide selection of nail size for the femur [17]:

- diameter of IM canal × 0.4;
- (diameter of IM canal/2) – 1;
- based on age (3 mm for children < 7 years old; 3.5 mm for 7–10 years; 4 mm for > 10 years).

In the tibia, 3–4 mm wide nails are used and in the forearm, 2–2.5 mm ones. These dimensions are trickier to measure on digitized radiographs with reduced image sizes, which can lead to errors when sizing the nails.

The nail must be as long as possible, while taking into account the most distal possible insertion point relative to the fracture site, far away enough from the perichondrial ring of LaCroix. The intramedullary end must anchor itself far enough into cancellous bone to conserve the biomechanics of the construct. The nails are bent manually until symmetric and the curve located over the fracture site.

4.1.3. Main indications

4.1.3.1. Lower limb. This method was first used in the femur. Ascending retrograde nailing is preferred except in cases where the distal end of the femur is fractured. If descending anterograde nailing is needed, epiphysial anchorage with individual paths for each nail is acceptable. The minimum age is defined by the limits of diaphyseal remodelling, with capacity being greatly reduced after 6–7 years of age. Starting at this age, standard fracture fixation should be considered. Exceptions are polytrauma patients, pathologic fractures or ones with a pre-existing conditions (neurological, congenital) or significant fracture instability that is not adequately controlled by conservative treatment (casting).

This construct may not be stiff enough in teenagers. The need for stability and risks of fracture impaction, especially when the fracture is comminuted, has led to two further improvements:

Use of end caps that are screwed at the distal end of femur rods or proximal end of tibial nail. This technique avoids fracture site impaction or nail subsidence upon active muscle contraction (Fig. 2).

Development of rods especially for trochanteric insertion in teenagers.

The upper limit for FIN indications is a function of skeletal maturity and patient weight. Traditional nails (with or without locking) and their entry points are dangerous at this age because of the risk of femoral head necrosis or femoral neck non-union (Fig. 3). Tibial fractures are rarely treated by FIN; casting is usually the preferred method. In teenagers, the technique is limited by the possibility of nailing, but this is not an option until the tibial tubercle is completely fused, because of the risk of genu recurvatum.

4.1.3.2. Upper limb. The proximal humerus has such a good remodelling capacity that indications for surgical fixation are rare. Mid-shaft fractures are a good indication as an alternative to the usual cast treatment. Intramedullary nailing at this location induces the risk of skin-related complications. FIN is used in a limited manner for supracondy lar fractures. This is a very demanding but effective technique. With FIN, the elbow does not need to be immobilized.

Indications for FIN in the forearm have previously been described in detail [18]. Since the ulna and radius have a low remodelling capacity, closed reduction must provide in anatomic alignment and 3 months of immobilization is required. This explains why FIN is widely used in children above 8–10 years of age. In these cases, only one nail is placed in each bone; the intersosseous membrane links the forearm frame together. If fluoroscopy is not
available or reduction is difficult, a small incision can be made over the fracture site to help insert the nails. The nails must be left in place 6 months before being removed.

4.1.4. Complications
Flexible IM nailing has the justified reputation of being reliable. Complications are rare if certain technical rules are followed closely. In 2001, Lascombes reported a 4% surgical revision rate (re-cutting of nails, etc.) and 0.1% sequelae rate [17]. A 0.4–0.7% infection rate was reported at the 2008 SOTEST meeting, including deep osteomyelitis away from the fracture and infection on the nails. Skin problems occurred in 14% of cases, mainly with humerus or tibia fractures, but also in the femur if the nails are curved distally. A comatose or poor-spirited child who does not regain mobility fast enough is at risk for skin-related complications. Less than 1 cm of leg length inequality has been found in isolated femur fractures. Repeated fractures are all too common in the forearm if the material is not left in place for at least 6 months.

Other complications are due to technical errors. Rotational errors are always possible with femur fractures. The most common technical pitfalls are:

- wrong nail size chosen (Fig. 4);
- nails too short;
- nails inserted in the wrong direction (Fig. 5);
- nails were not bent symmetrically (Fig. 6);
- wrong nail orientation (Fig. 7);
considered reduction, over time. 

- inaccurate evaluation of the patient’s age or size, especially with teenagers (Fig. 8);
- not achieving a double secant arc and having the nails cross multiple times.

Problems encountered during surgery are often due to patient-related issues or lack of reduction before initiating nail insertion. The surgeon should not rely on the curved tip to achieve fracture reduction, as its true purpose is to direct the nail. Reduction must be performed on the traction table or using external manoeuvres. In some cases, such as 15% of forearm fractures, the skin can be incised over the fracture site. Delayed union and non-union are rare, but can occur because of infection, an incision made over the fracture site and especially a technical error.

The material can be removed about 4 months after being inserted, once the fracture callus has signs of an intramedullary canal. Forearm fractures are the exception – the nails must be left in place for 6 months to avoid repeated fractures.

4.2. Orthopedics: locking compression plate

Since pediatric orthopedic surgeons encounter a variety of acquired or secondary skeletal deformities, the treatment strategy often involves an osteotomy. Many are performed at the bone ends in the metaphysis area and are said to proceed at a snail’s pace, while keeping with the rules of pediatric osteotomy, and are fixed with K-wires or staples. These are often performed as a realignment procedure. Construct stability is aided by a cast, which is well tolerated in children. Union problems are rare, as long as the periosteum is carefully detached, preserved and even reclosed.

However, these techniques are not sufficient and even dangerous in older children and in teenagers, or in cases where extended immobilization must be avoided, such as a child with neurological impairment. Instead of a stable fixation, the goal should be to achieve a strong fixation. Fixation of osteotomy in the shaft has historically been ensured by long, stiff plates. Compression at the site has been a secondary focus. The disadvantages are soft tissue injuries, large scars and aggressive periosteal removal leading to excessive lengthening. Supplemental immobilisation induces muscle atrophy, as it does in adults.

The advent of locking compression plates is an important advance from a biological standpoint [6,19] and has also changed how postoperative care is performed. This is the not time or place to review how it was developed or extol its biological virtues, but it suffices to say that these plates are the equivalent of using external fixation internally. The construct is short and stiff, while still allowing the remainder of the shaft to remain flexible. The plate is not attached to the bone, thus the periosteum can heal. Immobilisation is not necessary. There is less postoperative pain. Rehabilitation can be started quickly and weight bearing is allowed almost immediately. These advantages are essential in cases of neurological diseases, especially if the treatment program includes multiple sites. Immobilisation is only needed for the associated procedures.
on tendons (Fig. 9). We do not want to go over the entire list of osteotomy indications, but short, straight four-hole plates (equal to having screw purchase on eight cortical surfaces) are placed on the femur, tibia or humerus to stop rotation.

The other indications for osteotomy are mainly in the hip [20]. The enormous range of available implants includes multiple variants of blade plates, along with screw-plates and anterior or lateral plates. Each surgical team has its preferred hardware and materials. But all of these systems still require use of hip-knee-ankle-foot orthotics after surgery.

The concept of locking screws has led to the development of pediatric hip plates specific to each age bracket (Figs. 10 and 11). Various models are available for all types of hip osteotomy proce-dures, along with proximal femur fractures. As mentioned previously, its main advantages are early mobilization and weight bearing. Triangulation of the proximal locking screws in the femoral neck ensures the screws will not pull out. If needed, correction can be made in all three planes.

4.3. External fixation

External fixation is indispensable for limb lengthening procedures, but also has some benefits when used as an alternative to internal fixation. The choice of fixator is made based on the fixation site, the surgeon’s preferences and training, and financial constraints. The pros and cons of each type of construct (ring, unilateral or combination) must be well understood and the surgeon must be familiar with the implantation techniques specific to each. Ring or circular fixators are mostly used with distal segments, while unilateral, straight-bar type fixators have multiple uses but often need a range of accessory pieces.

In trauma, use is limited to open fractures, revisions, and treatment of delayed union, although some have suggested using them in closed femur fractures. In orthopedics, other than in standard limb lengthening procedures, external fixation can be valuable in cases of multi-planar correction or staged osteotomy procedures. It also offers the possibility of gradual axial correction, through several alignment modifications or by asymmetric distraction, to avoid the risk of compartment syndrome in proximal tibial sites, for example. Correction of rotational deformity must be performed carefully because of the risk of compartment syndrome. In some cases, union is not achieved and the bone fractures again. External fixators would also be useful in tropical climates where casts are not as well tolerated (Fig. 12).

The ability to bear weight almost immediately stimulates the fracture callus and reduces the risk of thromboembolism in older children. Its drawbacks are related to the bulk of the device and the unsightly appearance. Extra care is needed with the pins to reduce the risk of infection.

4.4. Fracture fixation for specific backgrounds

We have already advocated systematically performing fixation in polytrauma patients, no matter the age, which goes against the usual rules surrounding childhood trauma cases [12].

Two specific pediatric scenarios will be described here as they both involve bone fragility.
4.4.1. Child with neurological impairment

Conservative treatments must be performed carefully since the dominant symptom is spasticity or hypertonia. Prolonged immobilization increases the risks of pressure sores, muscle-tendon contractures and rapid muscle atrophy. The immobilization period must be as short as possible, and rehabilitation must be started as soon as pain subsides. FIN-type fixation is more widely indicated, which will require shorter immobilization in non-walking children.

4.4.2. Osteogenesis imperfecta

Here, fixation has two goals – treat the fracture and prevent recurrence. The chosen fixation system must allow for growth. Telescopic nails [21,22] or sliding FIN [23] (Fig. 13) are the two main options. The former requires going through the joint, while the second risks inducing subcutaneous impingement, especially in the popliteal fossa. Both require going through the growth plates, but the risk of epiphysiodesis is limited by the permanent presence of the fixation material. However, the material must be changed as the child grows. Both systems are compatible with the staged realignment osteotomy procedures that are often required.

In tumour cases, FIN allows benign lytic bone lesions (simple bone cyst, aneurysmal bone cyst, fibrous dysplasia) to be protected (Fig. 14). It is compatible with modern treatments involving injection of bone marrow, absolute alcohol and corticosteroids. It is preventative or curative for pathological fractures. Depending on the patient’s age, “adult” type fixation hardware such as locked nails, gamma nails, screw-plates and others will then be used for permanent lesions. Diaphysis reconstruction after tumour resection has improved because of the technical advances described above, such as the use of massive grafts with or without vascularized fibular graft, the induced membrane technique (Fig. 15) or Ilizarov bone transport [24].

5. Pitfalls related to the growth plate: epiphyseal-metaphyseal fixation

Injury to the extremities often involves the joints and requires anatomical reduction, which is synonymous with surgery and fixation. The main complication is premature closure of the growth plate (epiphysiodesis), but necrosis and non-union are also possible. Although the appearance of complications depends on fracture type [25,26], time before reduction [27] and quality of the reduction [26], surgical treatment is strong source of risk factors relative to the type of material and surgical approach used.

A long skin incision, especially at the elbow, can induce devascularization of the fragment, especially if electrocautery is used excessively. Altered growth of the olecranon has also been described following tension band wiring [28]. These complications have been lessened through the development of percutaneous minimally invasive surgery and specific hardware.

The growth plate is the main target of hardware-related complications:
• compression induced directly or related to the activity of the cartilage [29]. A study performed on the distal femur of rabbits showed that the amount and duration of compression applied are the main factors affecting the activity of the growth plate. The initial compression provided by the fixation hardware and the delay before removing the material must be considered when new implants are being designed. Conversely, this reduced growth can be induced on purpose when epiphysiodesis is desired (screw fixation, staples, figure-eight plates), or intentional fusion of slipped capital femoral epiphysis by choosing larger diameter compressive hardware;

• size and volume of implants [30]. It has been shown in rabbits that the nail must be smaller than 2 mm in diameter to avoid altering growth. If we extrapolate these findings to the size of various growth plates in children, 1.8 mm is the maximum diameter that can be used on a medial malleolus, for example.

5.1. Treatment options

Based on the requirements described above, we must remember that using plate fixation is practically crime because it removes periosteum from the perichondral area and induces compression due to bridging of the growth plate area.

Options are:

• external fixation, especially ilizarov-type circular fixation, which makes it possible to not cross the growth plate or use pins, or provides the option of using olive K-wires to compact the fragments. The drawback is that it induces compression, thus must be removed early on. Implanting an external fixator in an emergency setting is tricky and the bulk and appearance of the construct can be off-putting;

• FIN meets the stated requirements. It is useful and effective in epiphyseal fractures without articular involvement, such as radial neck fractures [13]. A pointed nail, preferably a stainless steel one for better stiffness, must be inserted in a retrograde manner through the distal end of the radius. Its placement results in retraction forces being applied as it draws the periosteum tighter;

• K-wires: as mentioned above, the K-wire diameter cannot exceed 2 mm. Virtually no compression is induced. It is a stable construct, but not a strong one. It must always be accompanied by cast immobilization until union is achieved (Fig. 16). Remember that prolonged immobilization of a joint in children does not lead to stiffening. But without this additional immobilization, the construct is subjected to secondary displacement;

• screw fixation is used when the growth plate do not need to be crossed. The development of various diameter cannulated screws has led to the expanded use of percutaneous fixation. The main indications for small diameter screws are ankle fixation [31] (Fig. 17) and medial epicondyle fractures. Larger diameter screws are used for fractures of larger epiphyses (distal femur), femoral neck fractures, and by extension, slipped capital femoral epiphysis;

Fig. 15. First reconstruction step of the induced membrane technique after removal of femoral osteosarcoma. Use of a special teenager nail inserted via the greater trochanter.

Fig. 16. Fixation of a supracondylar fracture in the elbow. Typical pediatric construct for epiphyseal-metaphyseal fixation, which is stable but not solid. Additional casting is indispensable.

Fig. 17. Salter-Harris type IV medial malleolus fracture. Percutaneous fixation is made easier by the pre-surgical CT scan and use of cannulated screws.
6. To be complete

Osteotomy and fracture fixation does not always require metal hardware. Bone fragments can also be stabilized by other means.

- adjustable block stop wires (BBR): this is a fixation device with characteristics of both a screw and a K-wire developed by surgeons in Strasbourg, France. Available in 1.5 or 1.8 mm diameters, they allow the surgeon to cross the growth plate and adjust compression. The distal end is threaded for insertion in the cortex, and the stop slides along the K-wire until it is screwed in place. The K-wire is then cut to the appropriate length. It was initially developed as an alternative procedure to tension band wiring of olecranon fractures [32], which has been shown to negatively affect growth [28]. Only a minimally invasive posterior incision is needed, mainly to bury the ends (Fig. 18). These wires have contributed to the development of minimally invasive surgery in children. They can also be used in elbow fractures (condyle, epicondyle), ankle fractures and reattachment of fractured intercondylar eminence. The main drawback is the risk of skin impingement, which requires early removal of the material. Future developments should result in better control over compression.

Resorbable suture is useful for stabilizing some small fragments or reattaching epiphysial or apophyseal avulsions. The advent of titanium suture anchors loaded with large calibre resorbable sutures has broadened indications in children. Other than tendon transfer, which is outside the scope of this lecture, these techniques can be very useful with medial epicondyle fractures, intercondylar eminence fractures with lacing at the base of the anterior cruciate ligament, and ankle sprains with bone avulsion (talofibular ligament) (Fig. 19). Resorbable pins can even be used during certain osteotomy procedures, for example metatarsal osteotomy for hallux valgus.

7. Conclusion

Osteotomy and fracture fixation in children may appear easy or even simplistic for the junior surgeon. Growth is known to correct many defects. We have shown that this apparent simplicity hides certain traps, thus learning must never stop. Although we have a better understanding of biomechanics of bone, it is essential in understanding its biology so that healing is not compromised. New developments will combine our knowledge of micromechnics with advances in tissue engineering. Further research must be done in these aspects.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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