Pierre Lascombes

Flexible Intramedullary Nailing in Children

The Nancy University Manual

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With Contributions by

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Originally published: Embrochage centromédullaire élastique stable by Pierre Lascombes

ISBN: 978-3-642-03030-7 e-ISBN: 978-3-642-03031-4

DOI: 10.1007/978-3-642-03031-4

Springer Heidelberg Dordrecht London New York

Library of Congress Control Number: 2009933611

Cover design: eStudioCalamar, Figueres/Berlin

Printed on acid-free paper

Springer is part & Springer Science + Business Media (www.springer.com)

Foreword 1

At last, a book dedicated to ESIN (elastic stable intramedullary nailing for those rare people who would not yet know what this acronym means)!

Today, ESIN ranks as high as conservative treatment in pediatric traumatology. One may be surprised at the paucity of published material about such a widely used surgical technique. Since my book was released in 1984, many articles have been published in specialized periodicals, but very few works have been written on this specific topic. The technique itself is so simple that very few improvements have been needed, but the indications have significantly expanded. The extensive experience of all the surgical teams who have contributed to this book should help bring down a complication rate that is already very low.

Up to 1977, no therapeutic alternative was available for fractures that required accurate reduction or for which immobilization was not desirable. The potential risk of dreadful complications using stiff internal fixation systems developed for adult patients outweighed the risk of malunion associated with inadequate closed reduction.

And yet, at that time, answers had already been found. The development of ESIN consisted in adapting to pediatric needs ideas that had limited acceptance and no clinical application:

- Flexible internal fixation allowing for micromotions at the fracture site enhances development of callus.
- Preservation of periosteum and fracture hematoma is critical to callus formation.

Elastic nailing addresses the conflicting situation of having a very stiff device implanted in elastic bone tissue. Percutaneous insertion does not affect the environment of the fracture, and healing conditions are very similar to those of conservative treatment.

During the first few years, from 1977 through 1980, this technique was reserved for specific indications such as patients with multiple injuries or severe head trauma in whom cast immobilization or traction was impracticable.

As the quality of the results achieved in the Department of Pediatric Orthopaedics (headed by Prof. Prévot), University Hospital, Nancy (France) gradually improved in spite of difficult intra- and postoperative conditions, surgical indications for ESIN expanded. Later on, many surgical teams, French teams first and then foreign teams became interested in this method. Today, ESIN is considered as the "Gold Standard" in surgical treatment of pediatric fractures by most pediatric orthopedic surgeons around the world. As surgeons now have higher requirements with respect to anatomic outcome, ESIN indications have markedly expanded. Furthermore, patient comfort, which was not a top priority 30 years ago, is now taken into consideration. Additional factors such as the overall cost of treatment and the impact of treatment on school attendance and family life are also taken into account. Thus, after being regarded as “the best alternative for patients who did not respond favorably to conservative treatment,” this safe, highly effective technique has been increasingly used with patient benefit as a key element: rapid healing, better comfort, and minimal disturbance of life. Paradoxically, one of the main issues with ESIN is its apparent simplicity and the excellent patient tolerance of the device. ESIN mechanical principles are easy to understand and the technique itself looks rather straightforward. As a result, many surgeons think that they are perfectly able to perform ESIN procedures with just a basic knowledge of its main principles and without any specific training. This inevitably leads to a number of complications, which are of course readily attributed to the method, whereas they are only the result of insufficient training and lack of experience. Curiously, some awkward constructs often yield a successful outcome. This does not mean that one can do anything and that it is just a matter of placing two nails, not bothering about diameter, length, entry point or position of the nails. Poor results are consistently due to incorrect constructs or indications.

We wanted this book to be an educational tool with lots of figures to illustrate all the indications (and contraindications) of ESIN, delivering hints and tips and emphasizing pitfalls to assist surgeons in achieving an optimal construct for each type of fracture. Each chapter includes detailed information about all the complications that may occur, even if infrequent, which is extremely important as it is much easier to avoid pitfalls that are already known. Careful reading of the complications experienced by experts of this technique will hopefully spare ESIN users and their patients many problems and disappointments.

It is a pleasure and honor to write the preface to a book that fills a significant gap in the literature on pediatric traumatology, and is doomed to become a mandatory reference work in traumatology, which every library will want to have on its shelves.

Jean-Paul Métaizeau

Foreword 2

Those of us in the English-speaking communities of pediatric orthopedics should now be excited that the pioneering work of the French-speaking originators of flexible intramedullary nailing (FIN) or elastic stable intramedullary nailing (ESIN) has been made available in this English translation of the original French textbook. The real beauty of this textbook is to learn the basic concepts and specific techniques of FIN that were originally pioneered by Jean-Paul Métaizeau. His work has been continued by Pierre Lascombes and his present co-workers who have labored hard to collect and organize the principles and techniques of FIN into this valuable textbook.

The use of the FIN has been one of the major advances in the management of long bone fractures in the skeletally immature individual. It has revolutionized the manner in which these injuries are now treated. I was a part of that generation of orthopedic surgeons who, in the past, treated children with fractures of the femoral shaft with skeletal and skin traction requiring weeks of hospitalization. The ability now to be able to mobilize children with femoral shaft fractures within a few days of the injury has been a tremendous source of pleasure in my present management of these injuries. This ability to rapidly mobilize the extremities containing long bone fractures has been a blessing for the parents and patients, as well as the treating surgeons.

This textbook is extremely reader friendly. The individual chapters are clear and concise. The text is broken up into many small paragraphs with frequent subtitles that make it easy to speed read, a technique that most surgeons utilize when reviewing textbooks.

The reader will discover that this book contains a wealth of information. Needless to say, the most important sections are those chapters in the final part of the book, which deal with the various FIN techniques for each of the fracture types. However, in the initial part of this textbook, the reader is first exposed to the basic principles and other ancillary processes that are necessary for the successful management of these fractures utilizing FIN. The important concepts regarding the basic science, experimental studies, and biomechanics of FIN are outlined in great detail in the introductory chapters. There are some unique chapters that deal with subjects not found elsewhere in the pediatric fracture literature, such as the differences between the use of titanium and stainless steel implants, imaging techniques with an emphasis on minimizing exposure to both the patient and surgeon, and finally, a chapter dedicated to the protocol of informing the parents on how to deal with their child in both the preoperative and postoperative periods. Thus, the reader will have the ability to become well-grounded on the basic concepts necessary to achieve a successful outcome prior to applying the specific techniques of the individual fracture patterns.

The final chapters, which deal with the specific techniques of managing the various types of long bone fractures in the skeletally immature patient, are again extremely complete and well organized. In each of the chapters, there is first a review of the characteristics of the fracture type being discussed. This is then followed by a very complete discussion of the specific FIN technique utilized. There is a complete discussion of topics involved in the preoperative management such as positioning, surgical approaches, and selection of the implants. The specific surgical techniques are very well described with extremely clear illustrations. Many of the discussions of the specific surgical techniques contain little pearls that often disclose how to facilitate a reduction or improve the stability of the fracture immobilization. The discussions on complications are well organized into early, late, and those associated with the technique itself. At the end of each of the chapters dealing with the most common fracture types managed by the FIN technique, there are sample case reports. These are followed by three tables that summarize the material contained in the chapter:

1. The six key points in the treatment process.
2. A protocol for the postoperative management.
3. The suggested indications for the use of the FIN techniques for the specific fracture discussed in the chapter.

It is predicted that in the future this textbook will become a required reading for all those individuals undergoing postgraduate training in orthopedic surgery. In addition, this textbook will serve to upgrade those of us who have been treating our patients in the past with the FIN techniques without the benefit of all this valuable information.

Kaye Wilkins

Preface

For many decades up to the late 1960's, the treatment of the diaphyseal and metaphyseal fractures in children was exclusively conservative. At that time, the only significant textbook on children's fractures was that of Walter Blount, which was published in 1955. The ensuing development of surgical fracture treatment using plates and locking nails produced no real benefit in the treatment of fractures in growing bones.

In the late 1970's at the Nancy University Hospital - situated in the North East of France and serving a population of 2.5 million people - Jean-Paul Métaizeau, M.D. and Jean-Noël Ligier, M.D. developed the concept of flexible intramedullary nailing (FIN). The method, previously used in Seville Spain, is based on the use of two curved intramedullary nails introduced into the injured bone through the metaphyseal area far from the fracture itself as well from the physis. This mini invasive surgery obtained an excellent boney union while respecting the periosteal callus. The stability was adequate enough to avoid postoperative immobilization. A rapid rehabilitation was possible, which resulted in a shortened hospital stay and a rapid return to the stable environment of home, family, school and hobbies. This combination of physical and psychological benefits for a traumatized child otherwise encountering an unnecessary pause in his or her natural development was further complimented by the economical benefit to the hospitals, families and insurers.

Professor Jean Prévot and I then spread our large experience with the FIN procedure from the Nancy University Hospital to all of France and then throughout Europe. The success was immediate with a lot of excellent results. In North America, Dr G. Dean Mac Even was one of the first surgeons to note the advantages of this method. However, some complications were described mainly due to an insufficient comprehension of the method and to significant modifications of the original technique. We realized that more information was mandatory, specifically in each detail of the procedure such as choice of the frame, selection of the nails according to their diameter and their shape, surgical approach, reduction of the fracture, orientation of the nails, impaction of the nails and the fracture, end of the surgical procedure and postoperative treatment.

At the beginning of this new century, Professor Remy Kohler of Lyon, France pushed me to write the FIN technique. The French edition, published in 2006 by Elsevier France, contained the data of more than 25 years of experience, and of more than 2,000 FIN procedures in our Department of Pediatric Orthopedics in the Nancy University Hospital. The great number of technical drawings, X rays and clinical cases allowed surgeons a more precise understanding of the technique and the strategy. A large part was dedicated to complications and how to avoid them.

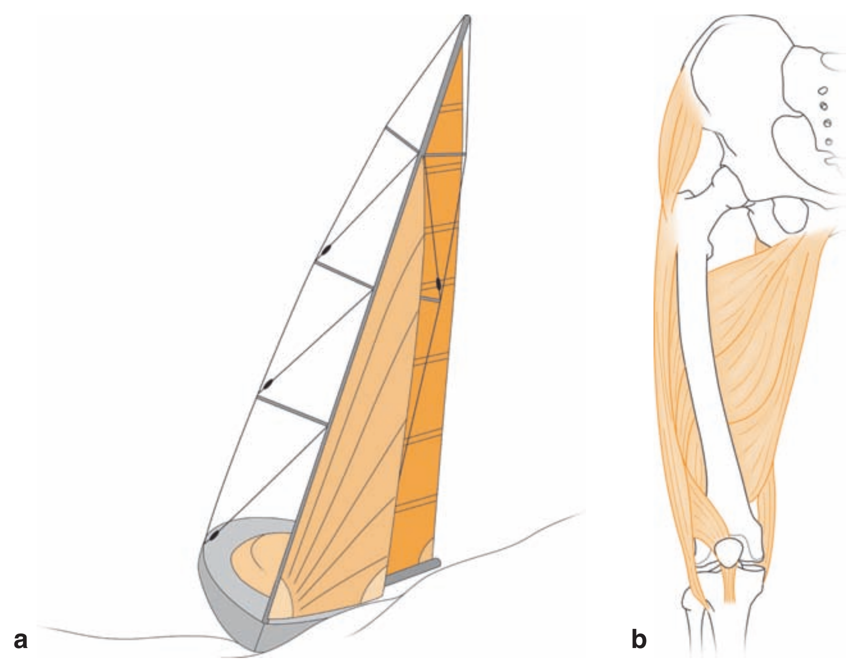
Colleagues from North America, notably Dr. Kaye Wilkins of San Antonio, insisted that the information contained in the book should be made available to Anglophone surgeons as well. I wish to pay homage to Thomas Roumens and Mary Kenny who initiated this English edition entitled: FIN, the Nancy University Manual. With this translated and improved edition, my sincere wish is to make the indications and the technique of the FIN procedure as comprehensive as possible so as to contribute to excellent fracture care of our children.

Nancy, France Professor Pierre Lascombes, M.D.

Acknowledgements

I thank a number of people who have helped in the realization of this book:

- Jocelyne Dieng for the translation from French to English
- Andreas Walker for the drawings
- Kirsty Salisbury for the editing
- Mariette Saint Pol for her help with documentation
- Mary Kenny for her encouragement
- Thomas Roumens, without whom the realization of this book could not have been achieved



"Just as the stays support the mast of a sailboat, so do the muscle masses support the skeletal frame."

Contents

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Part I

General Considerations

1 Introduction

Pierre Lascombes

1.1 Introduction

There is a wealth of published literature on intramedullary nailing. With current locking designs, intramedullary nailing indications have been expanded to include a large number of diaphyseal and even metaphyseal fractures in adult patients. Küntscher was the one who pioneered the concept [1], but extensive work had been previously carried out on nailing or pinning techniques in which the nails/pins did not fill the entire transverse section of the diaphysis. The so called alignment nailing technique was widely used by Rush [2] after World War II. These bulky devices were used in forearm fractures, where they allowed maintaining a precarious reduction without any control of the rotatory stability, which made it necessary to use external immobilization. Furthermore, they were associated with postoperative complications such as skin ulceration at the insertion site. Bundle nailing for metaphyseal fractures using two, three, four, or even more thin elastic nails was widely used by Hackethal for treatment of fractures of the upper end of the humerus [3], and by Ender for femoral neck fractures in the elderly [4]. Ender nailing almost completely disappeared from the therapeutic armamentarium due to the incidence of rotational malunion of the femur and nail migration, in favor of more advanced devices. But the notion of "elastic" osteosynthesis was retained, and was used for fixation of certain types of fractures like tibial fractures [5]. Actually, it was even incorporated into the concept of the Ilizarov external fixator, as Ilizarov had fully demonstrated that when traction-compression forces are applied to bone with intact periosteum and blood vessels, healing occurs regardless of the circumstances [6].

The notion of stability can be very simply expressed in terms of stable or unstable equilibrium: a body at rest is in stable equilibrium if, when slightly displaced, it tends to return to its original position of equilibrium; a body in unstable equilibrium will sooner or later return to stable equilibrium. The best illustration of this is the sailboat with its keel (Fig. 1.1).

In the late 1970s, Dr. Jean-Paul Métaizeau (young Chief Resident), Jean-Noël Ligier (Resident), and Prof. Prévot (Head of the Department of Pediatric Orthopedics, University Hospital, Nancy) were working out a way to stabilize femoral fractures in children. They took up the idea and tailored the system to children's specific needs. Eventually, on September 27, 1979, Hubert Lanternier and J.N. Ligier performed their first ESIN/chk if full form needs to be given in a 9-year-old child, Mathieu, who had been hit by a car while riding a bicycle. Four 3 mm diameter stainless steel nails were used (Fig. 1.2).

Early constructs used three or four nails; there was even a "Tour Eiffel" frame design. Gradually, the idea of using only two elastic nails with opposing curves took shape. Within a few months, a finalized surgical technique was developed that had the additional advantage of eliminating the need for cast immobilization. On March 17, 1980, Frédéric who had been injured during a football match was operated on by J.P. Métaizeau, who used "only" two nails (Fig. 1.3). However, in the two above-mentioned cases, a long-leg cast was associated with ESIN.

Meanwhile, J.N. Ligier was defending his M.D. thesis in which he reported on the treatment of subtrochanteric fractures in adults by elastic nails [7]. At a time when the rigid internal fixation concept supported by the Swiss Association for Osteosynthesis (AO) was the "Gold Standard" in fracture fixation, and the concept of compression-distraction osteogenesis developed by Ilizarov had not yet been popularized in Western Europe, it was a real provocation.

P. Lascombes, *Flexible Intramedullary Nailing in Children,*
DOI: 10.1007/978-3-642-03031-4_1,

As early as 1980, ESIN indications expanded dramatically. It was first used in diaphyseal fractures: femur [8], and then tibia, both bones of the forearm [9], and humerus. Later on, metaphyseal fractures were also stabilized using different methods: Hackethal, Ender, or even Foucher for the fifth metacarpal [10]. Although management of humeral neck fractures was complication free [11], it was a different story with supracondylar fractures of the elbow, which are associated with a high risk of malunion, and radial neck fractures, which carry a high risk of postoperative necrosis. J.P. Métaizeau had the idea of using the nail itself as a reduction tool: impaction of the nail into the radial head, rotation of the nail to reduce the head, and then fixation [12, 13]. As for supracondylar fractures, P. Bour had no difficulty in proving that the antegrade divergent construct designed by Métaizeau outperformed all the other internal fixation methods used in children, and minimized the potential risk of malunion since anatomic reduction is mandatory to obtain a functional construct [14, 15].

Our total number of cases has kept increasing over the years, thanks to all the residents and chief residents who performed at the Clinique Chirurgicale of Nancy, and to whom I am very grateful. Since 1981, I have followed more than 1,700 patients treated with ESIN. I have also organized instructional courses, first at a regional level, then national, European, and finally international level. This is how the ESIN method has gradually spread worldwide. It has become so popular that now surgeons often want to share their own tips and tricks with us! The result of this popularity is that in many countries the original acronym “ESIN” [16] has been changed to “FIN” (Flexible Intramedullary Nailing), which we have eventually adopted to reach a consensus view. As a matter of fact, “stable” does not have the same connotation for all surgeons: some will consider the physics meaning “stable equilibrium”

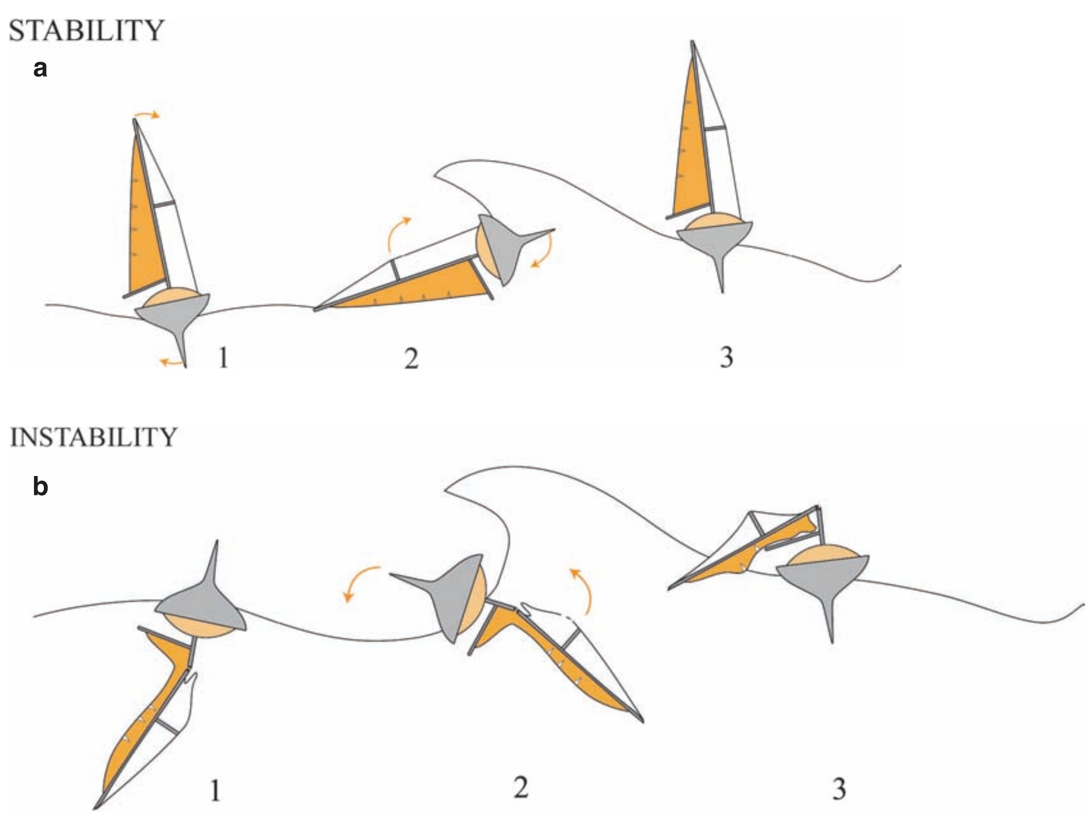

Fig. 1.1 The behavior of a sailboat in waves illustrates the notion of stability (**a**) and instability (**b**) 1: initial position; 2: displacement; 3a: return to the initail position = stability; 3b: change to another position = instability

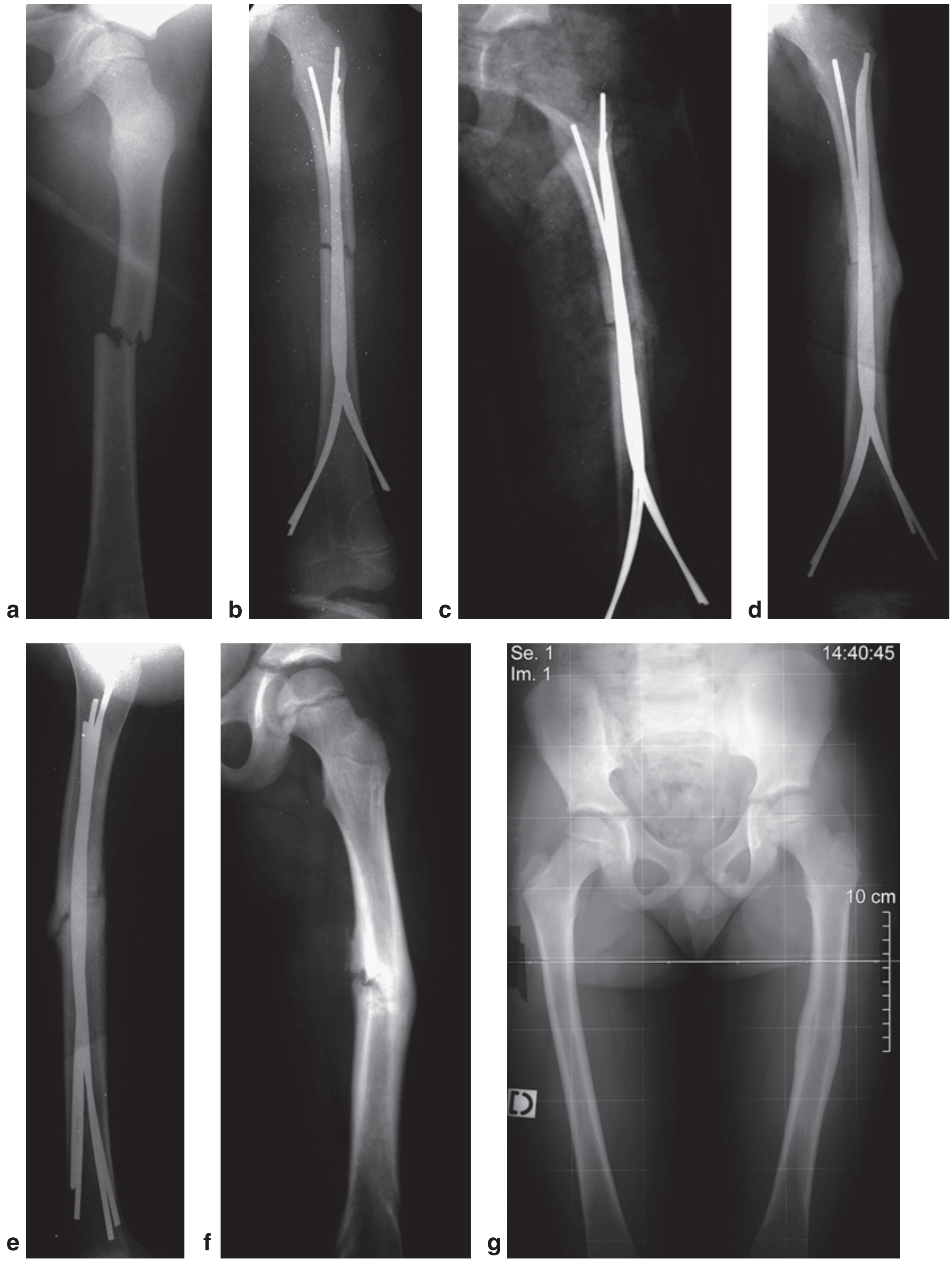

Fig. 1.2 M. B., a 9-year-old boy, was riding a bicycle when he was hit by a car coming in the opposite direction. He sustained head trauma and closed transverse fracture of the middle third of his *left femur* (**a**). On September 27, 1979, four 3 mm intramedullary nails were inserted using lateral and medial supracondylar approaches according to the Ender technique (**b**). Additionally, a long-leg cast was applied for 2 months (**c**). Follow-up radiographs clearly showed callus formation on the lateral aspect of the femur (**d**, **e**). Nails were removed at 5 months. Varus angulation of 10° (**f**). At 18 months, the fracture was united with a residual varus angulation of 5° and leg length discrepancy of 15 mm (**g**)

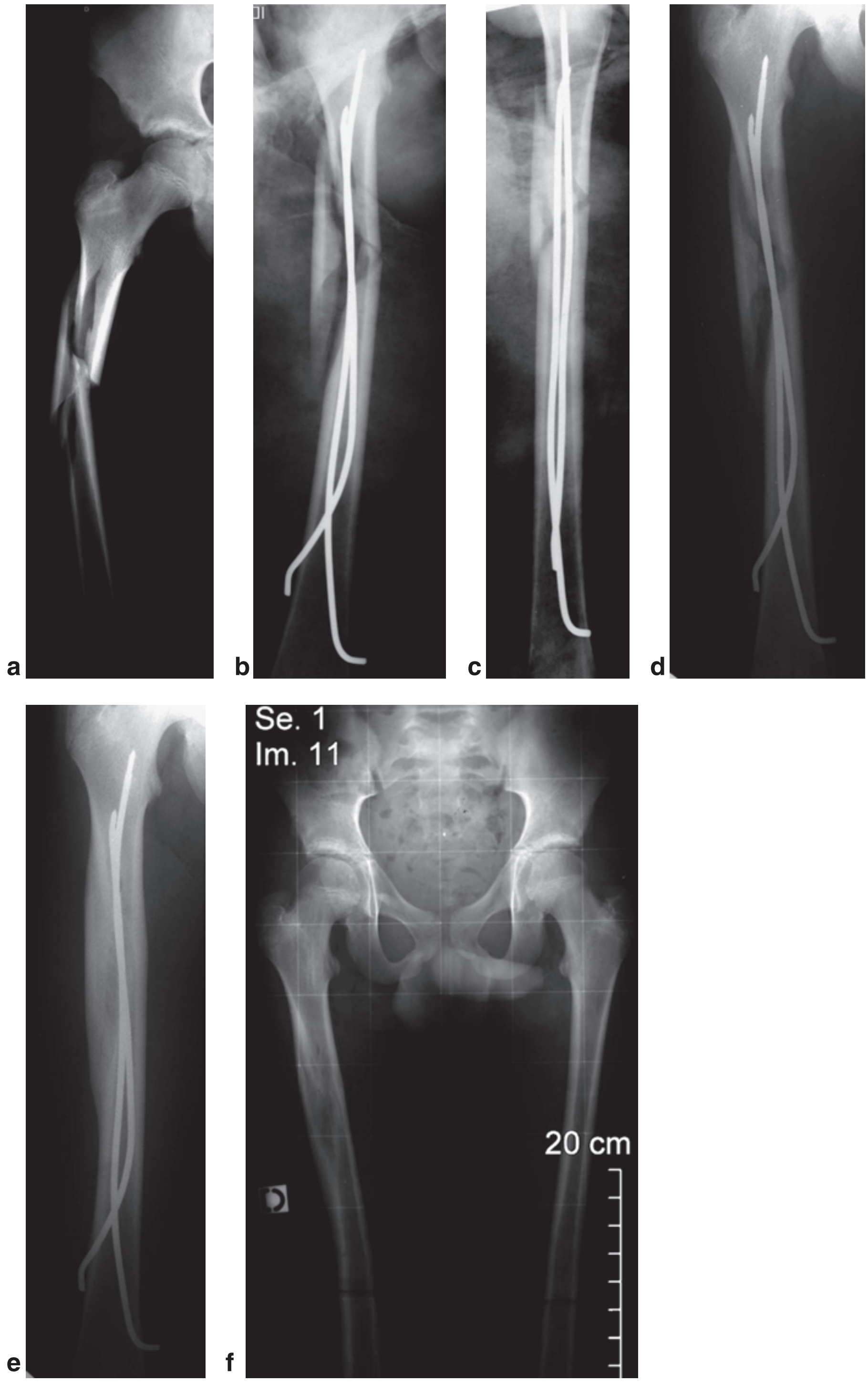

Fig. 1.3 F. T., a 13-year-old boy with spiral fracture (with a third fragment) of the *right proximal femur* sustained during a football match (**a**). On March 6, 1980, after a few days of traction, closed internal fixation was performed using two threaded K-wires and the child was immobilized in a long-leg cast for 6 weeks (**b**, **c**). Stiffness developed in the knee: at 2 months, aggressive rehabilitation was necessary. Partial weight bearing at 2 months, full weight bearing at 3 months (**d**). Six months later, bone union was achieved (**e**). K-wires were removed. Eighteen months later, the boy had normal knee motion but his right femur was 2 mm shorter than his *left femur* (**f**)

while others will understand "stiffness." Therefore, in the next chapters, we shall use FIN.

The FIN method, also termed Métaizeau technique [17, 18], Nancy technique [19, 20], or ESIN technique (mainly in Europe) [21] was introduced in the 1980s through instructional course lectures (which we cannot all mention here), numerous medical theses [14, 21–24] and scientific essays. In addition, K. Parsch published, in the 1990s, a detailed history of this method in the treatment of femoral fractures in childhood [25], and informed us of a publication conducted by Moroté Jurado in 1977 (Seville team, Spain). The technical protocol was identical to that used in Nancy. The series included 100 diaphyseal fractures of both bones of the forearm [26] (Figs. 1.4 and 1.5). To recognize the Spanish authorship of this study is only fair.

Almost 30 years after its introduction, the FIN method has now become a universal way of treating fractures. Early criticisms and doubts were eventually laid to rest, and both strategic and technological improvements were made. Now, children can benefit from a low-morbidity functional surgery, which does not interfere with the growth process. The outstanding advantages of FIN over other fixation systems such as intramedullary locked nails, screw plates, and external fixators have long been recognized, although there are still specific indications for each of these systems. However, training of new generations remains a priority, which has also inspired this book.

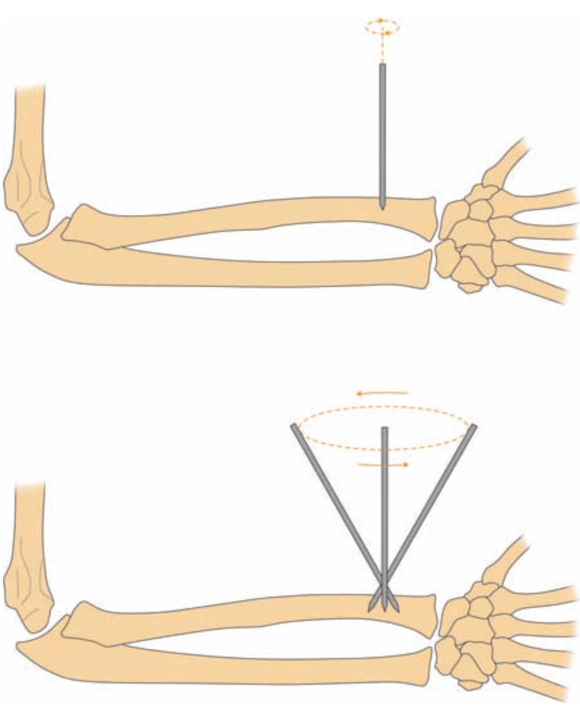

Fig. 1.4 Ideal entry site. Technique used by Perez Sicilia [26] to create the entry hole in the lateral cortex of the radial metaphysis

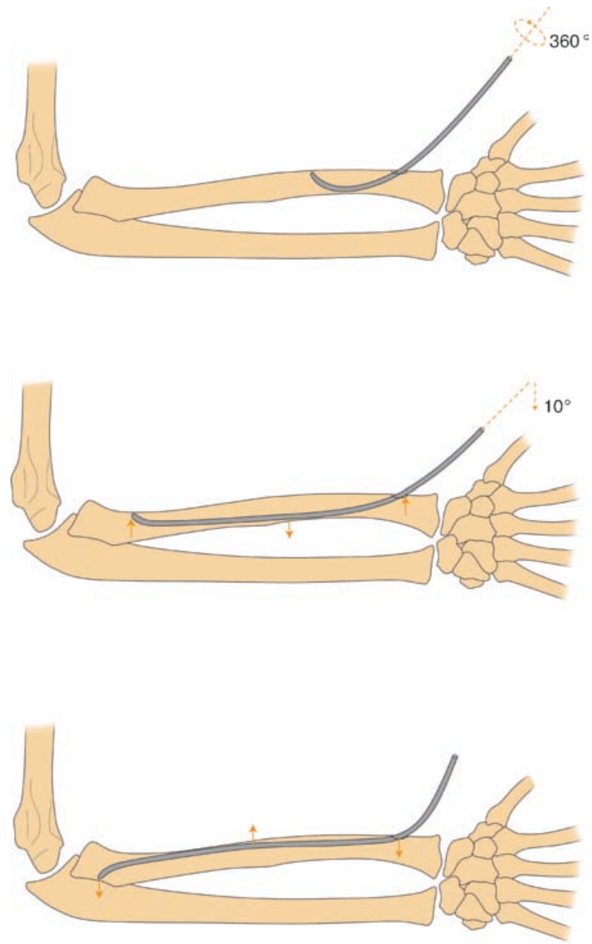

Fig. 1.5 Guided insertion and rotation of the nail for proper stabilization of the bone fragments, according to the Perez Sicilia's technique [26, 27]

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2 Experimental Studies

Dimitri Popkov and Pierre Lascombes

2.1 Bone Healing in Rabbits

Flexible Intramedullary Nailing (FIN) is a closed internal fixation method based on the principles of primary fracture healing of nonoperative treatment. Initial fracture hematoma and periosteum, which is largely preserved, are included as part of the well-known fracture–repair process. Our experimental study in rabbits conducted in 1985 [1] confirmed that fracture healing with FIN is predominantly by periosteal callus, which forms outside of the fracture.

2.1.1 Materials and Methods

Experiments were carried out at the Laboratory of Experimental Surgery headed up by Prof. Bénichoux, University Hospital, Nancy, in 1985 and 1986. Fractures were created in rabbit tibiae under general anesthesia. Different types of mid-shaft fractures were randomly produced (i.e., simple, complex, comminuted).

These fractures were treated by closed internal fixation using two 1 mm stainless steel nails inserted through the proximal or distal metaphysis. No external immobilization was used and weight bearing was resumed immediately.

Radiographs were taken at weekly intervals for 6 weeks, then at 3 and 6 months, depending on the age of the animal at sacrifice. Histological studies were performed at d 14, 21, and 45. Bone samples were embedded without prior decalcification in methylmetacrylate resin (Dr. Hervé Membre, Laboratory of Histology headed up by Prof. Grignon, University School of Medicine, Nancy).

All fractures united and rabbit activity did not seem to be disturbed during that period: no complications, no nonunions, no sepsis occurred.

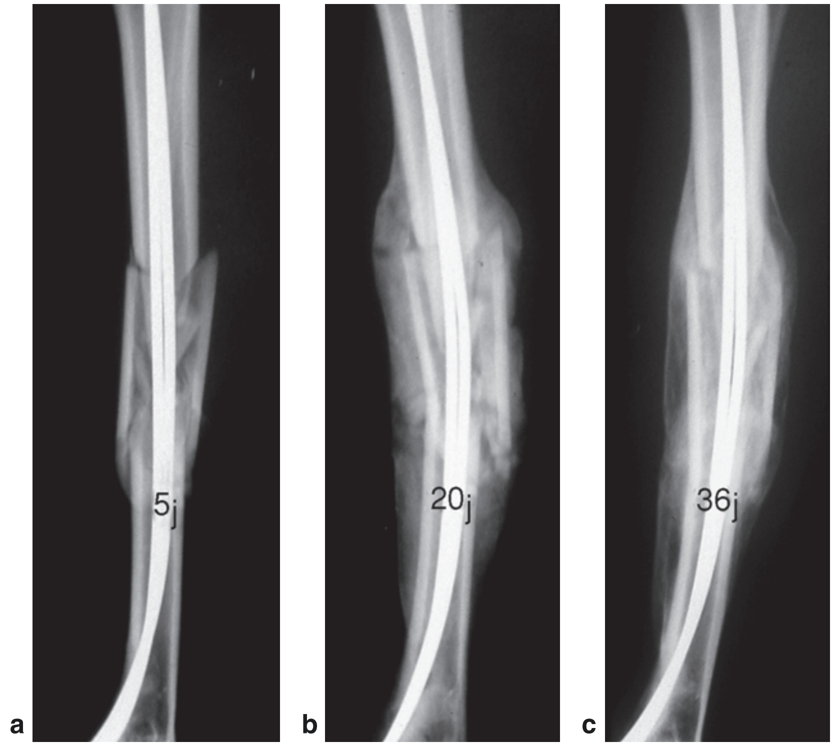
2.1.2 Results

2.1.2.1 Radiographic Results

At week 1, no signs of ossification could be found (Fig. 2.1a), but on the 14th day, radiographs of simple fractures showed formation of dense periosteal bridging callus. Cortices were not yet healed, but bridging callus was quite strong. Radiographs of comminuted fractures began to show periosteal callus of inhomogeneous structure, and signs of intramembranous ossification (Fig. 2.2a). At week 3, the periosteal region was expanded; periosteal callus formed a sheath around bone fragments in comminuted fractures, and led to solid union in some simple fractures (Fig. 2.3). Furthermore, patency of the medullary canal was maintained due to the presence of the intramedullary nails (Figs. 2.1b and 2.2b). At 1 month, simple fractures were radiographically healed. Comminuted fractures were sheathed in a homogeneous external bridging callus, and gave an impression of stability, but the cortices were not yet fully healed (Fig. 2.2c). At week 6, good quality callus with a homogeneous structure was present, but not all cortices were fully healed (Fig. 2.1c) as evident in MRI (Fig. 2.4). At 3 months, all fracture sites were radiographically consolidated: presence of intramembranous ossification, cortical bridging, and intramedullary callus. At 6 months, the remodeling process was well under way but external

P. Lascombes, *Flexible Intramedullary Nailing in Children,*
DOI: 10.1007/978-3-642-03031-4_2, © Springer-Verlag Berlin Heidelberg 2010

Fig. 2.1 Comminuted fracture of the femoral shaft (rabbit) treated by flexible intramedullary nailing (FIN). Control X-rays taken at 5 days (**a**), 20 days (**b**), and 36 days (**c**)



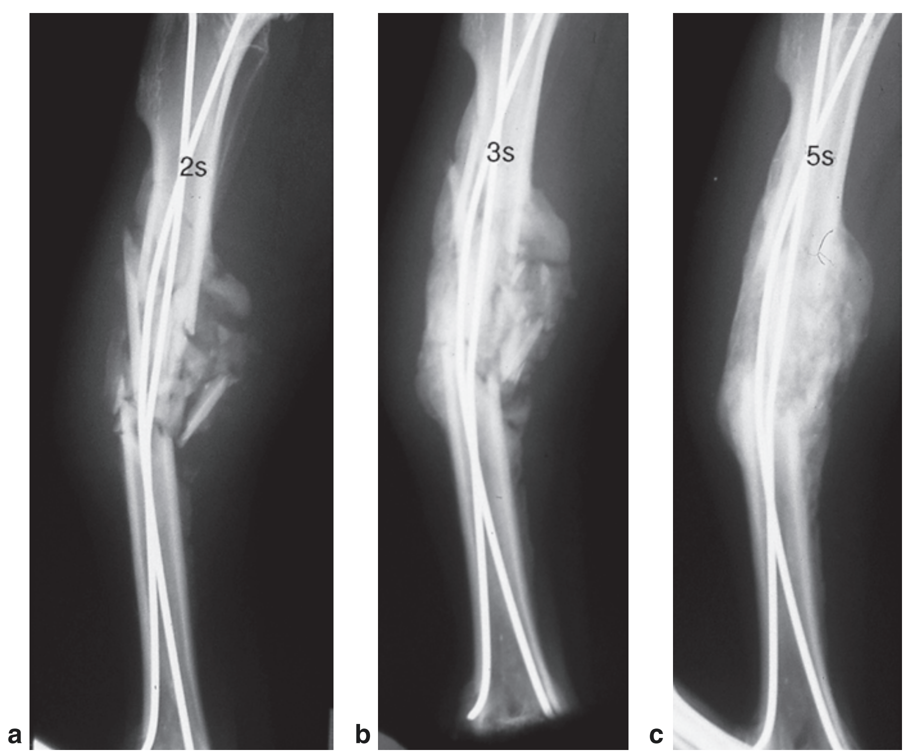


Fig. 2.2 Comminuted fracture of the femoral shaft (rabbit) treated by FIN. Control X-rays taken at 2 weeks (**a**), 3 weeks (**b**), and 5 weeks (**c**)

Fig. 2.3 Transverse tibial fracture (rabbit) treated by FIN. Union achieved at 20 days

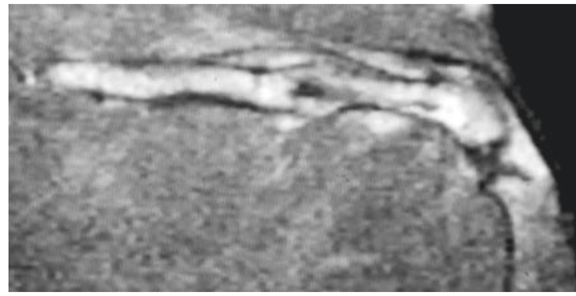


Fig. 2.4 MRI image of a femoral fracture (rabbit) at 6 weeks [courtesy of Dr. J.L. Lemelle]

callus was still present. Although cortical bone was not yet fully reconstructed, its quality seemed excellent (Fig. 2.5).

Fig. 2.5 Complex tibial fracture (rabbit) treated by FIN. Remodeling process at 6 months

2.1.2.2 Histological Results

On the 14th day, examination of the slides revealed the following:

- Periosteal callus consisted of small free-standing trabeculae of new bone laid down upon the fibrous tissue. Tissue fibers defined the trajectories of the trabeculae. These trabeculae were already interconnected and had specific orientation patterns: at some distance of the fracture site, they were oriented perpendicular to the adjacent cortex, whereas at the fracture site, they were parallel to the long axis of the bone. A few islets of cartilage could be seen at the periphery of callus, sometimes creating a narrow bridge between the ends of the cortices.
- There was no sign of cortical bone resorption and no abnormal osteoclastic activity.
- There was excellent medullary vascularization, and many blood capillaries were over 0.2 mm in diameter. One striking finding was the presence of bone islets and trabeculae around the intramedullary nails.

To give an idea of the intensity of periosteal reaction, let's just say that it doubled the diameter of the bone shaft (including both cortices). Mean diameter of the diaphysis was 6 mm, of the medullary cavity was 3.2 mm, of each intramedullary nail was 1 mm, and that of the periosteal callus was 11.5 mm.

The third week (Fig. 2.6):

- Peripherally, bone trabeculae got thicker and numerous interconnections were observed. Intense osteoblastic activity was characterized by a large number of osteoid rims and fence-like cell arrangement.
- As regards cortices, neither resorption nor reconstruction was noted: bone ends did not seem to take part in the repair process.
- On the other hand, endosteal callus trabeculae extended from both ends of the fragments and formed a small bridge.

At the end of the first month, hard callus maturation was still going on via perfectly interconnected primary bone trabeculae. Intense osteoblastic activity was observed, whereas no osteoclastic resorption seemed to take place.

After 6 weeks (Fig. 2.7):

- There was no real change in endosteal and periosteal ossification, and in any case, no remodeling. And yet, when examined under polarized light, bone trabeculae had a pseudo-lamellar appearance characteristic of bone repair.
- Callus was peripherally delimited by a thin layer of lamellar bone that encompassed the entire fracture site.
- Callus, consisting of small, highly interconnected trabeculae began spanning over the fracture gap. It was not yet remodeling but simple primary ossification, a kind of "osseous anastomosis" (Fig. 2.8).

At 3 months, peripheral resorption was initiated, even though the osteoblastic activity still predominated.

Fig. 2.6 Histologic appearance at 21 days. Note the external callus, endosteal callus, and bone trabeculae along the intramedullary nail (femur – rabbit)

Fig. 2.7 Histologic appearance of a comminuted fracture at 42 days. Note the abundant periosteal callus, and cortical callus formation (circled area) [femur – rabbit]

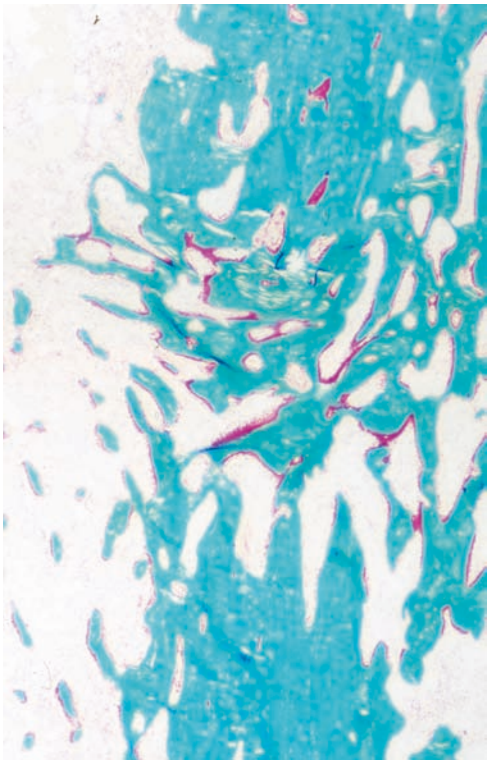


Fig. 2.8 Higher power view of Fig. 2.7 shows bridging process at 6 weeks (femur – rabbit)

There was a very low osteoclastic activity, without which remodeling cannot take place.

2.1.3 Conclusion

With FIN, fracture healing occurs via an initial fibrous tissue on which trabeculae of new bone are laid down to form periosteal callus (external callus). The cartilage callus phase is not mandatory; actually, it is often bypassed. The next stage of bone repair is the formation of endosteal callus and medullary ossification along the intramedullary nails. Then, bridging external callus forms to establish contact between the fragment ends, but the strong lamellar bone is still not involved in remodeling.

The chief advantage of FIN is to promote rapid healing while preserving the patency of the medullary canal, thanks to the presence of the intramedullary nails, which further minimize the risk of mid-term recurrent fracture.

2.2 Combined FIN/Ilizarov Method for Bone Lengthening in Dogs

Based on our extensive experience with the Ilizarov lengthening method, we have demonstrated that one of its fundamentals is preservation of periosteum and intramedullary circulation. Furthermore, quality of the regenerate depends on the lengthening rate, which can be individualized [2]. Automatic high-frequency lengthening and compression of the regenerate immediately after the lengthening period provide optimal conditions for tissue regeneration, and result in significant reduction of the external fixation period [3]. Works have been done to demonstrate the prominent role of periosteum in distraction osteogenesis [4, 5]. Intramedullary nailing provides a strong elastic frame, which enhances the formation of periosteal callus. Additionally, as the two intramedullary nails do not completely fill the medullary cavity, endosteal callus formation is not inhibited. We have worked on the FIN concept to ensure compatibility with the Ilizarov method for limb lengthening. The following study conducted in dogs allows to better understand our philosophy, and evaluate all the benefits of this combined method.

2.2.1 Materials and Methods

This study was conducted in 14 dogs of various breeds, aged 1 to 4 years, with an average weight of 18.8 kg. Mean length of tibia was 187 mm. The Ilizarov fixator used consisted of two distal rings and two proximal three-quarter rings, connected by threaded rods. Both percutaneous osteotomy of the fibula and osteoclasis of the tibia were performed in the middle third of the diaphysis. The FIN construct used two 1.5 mm nails with opposing curves (Fig. 2.9). Both nails were sharply contoured, and their tips bent to 30–40° over a length of 2–3 mm. Their initial curves were identical, with apex located in the midsection. Both nails had blunt tips. Two slightly oblique entry holes were made with an awl in the superior portion of the proximal metaphysis. The first nail was hand pushed into the medullary canal, then across the osteoclasis and down to the distal metaphysis, as far as possible into the cancellous bone. The second nail was inserted in the same manner, on the opposite side of the bone. The final

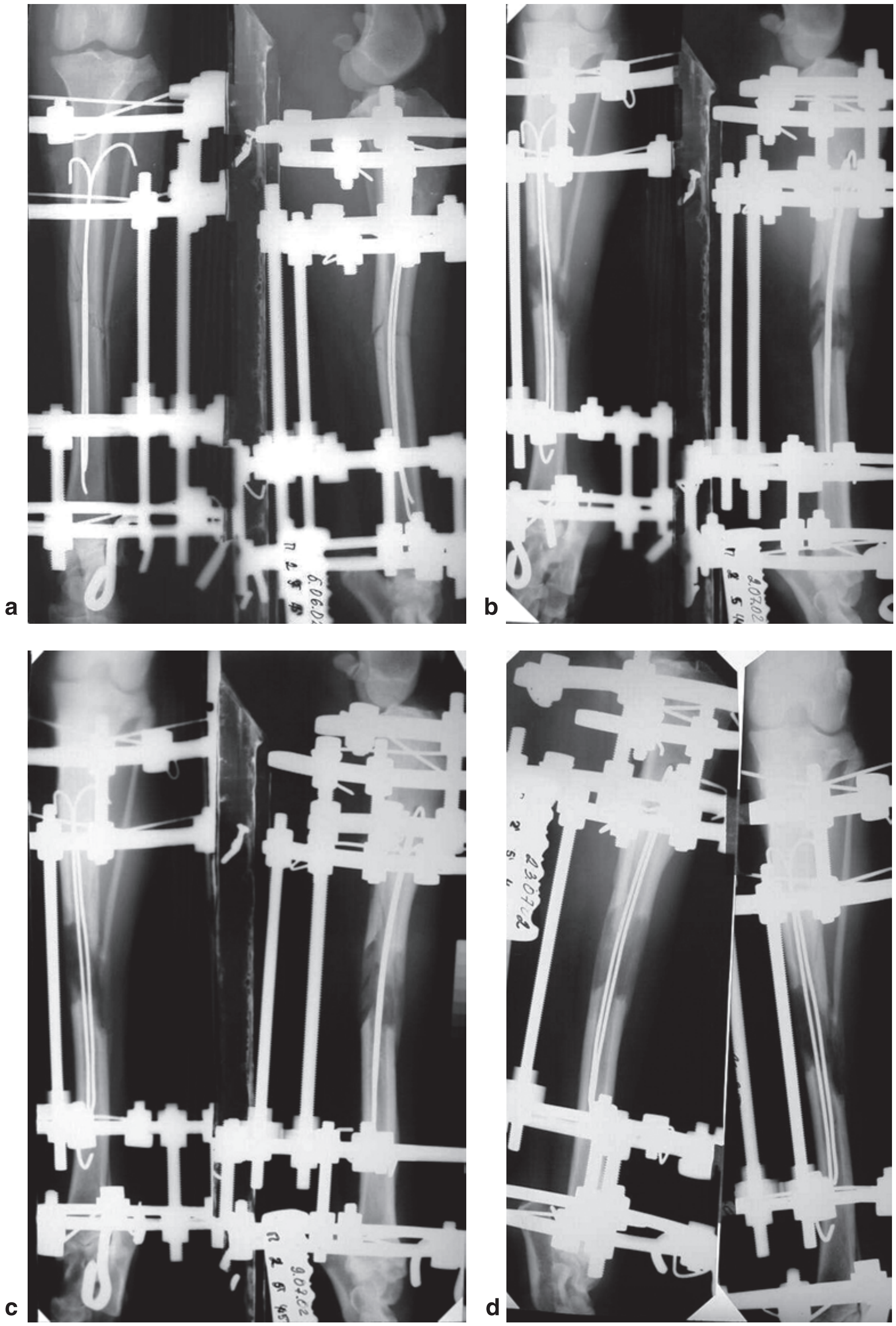


Fig. 2.9 Radiograph of the *right tibia* (dog).Tibial lengthening by combined Ilizarov/FIN: (**a**) Ilizarov fixator and intramedullary nails in place, osteoclasis of the tibia; (**b**) X-ray taken after 21 days of lengthening; (**c**) X-ray taken after 28 days of lengthening (end of lengthening period). Note the intense and extensive periosteal reaction, and a growth zone with numerous bone trabeculae. Thirty millimeter lengthening; (**d**) Complete healing achieved after 14 days of external fixation, external fixator removed

e

Fig. 2.9 *(cont.)* (**e**) X-ray taken 15 days (d 63) after removal of the external fixator and resumption of weight bearing

construct consisted of two nails with opposing curves positioned in the same plane. The free ends (trailing ends) of the nails were cut relatively short and bent to about 45–60° to prevent nail migration during distraction. The skin was closed in one layer. Distraction was initiated on the fifth day in all dogs (Fig. 2.9). Duration of lengthening was 28 days. Mean distraction rate was 1 mm/day (in four steps) (Table 2.1). However, as control X-rays showed extensive bone regenerate, the distraction speed had to be increased at d 8 in 4 dogs, d 15 in 3, and d 21 in 1. Early healing occurred twice after about 21 days of lengthening, and twice after about 28 days: in two cases, distraction resulted in fracture of the regenerate that had already consolidated (Fig. 2.10), whereas in the other two cases, the newly regenerated bone was already very strong. The 28-day lengthening period was followed by the external fixation period. The external fixator was removed after 15 days (sixth week) in eight dogs and 30 days (eighth week) in four. All the dogs could bear weight right after removal of the external fixator without any limb protection.

Results were evaluated based on the radiographic appearance of the regenerate. Control X-rays were performed on a weekly basis throughout the distraction period, and thereafter, at 45 days, 60 days, and after removal of the intramedullary nails. Arteriographies were performed in some dogs after sacrifice: at d 5, 39, and 63. Additionally, bone regenerates were histologically studied.

2.2.2 Results

Radiological changes indicated intense and extensive bone regeneration, which forced us to increase the distraction speed in some dogs. Newly formed bone was visible on radiographs after about 7 days of lengthening. At this stage, the regenerate had an inhomogeneous structure with localized areas of increased bone density. Extensive periosteal reaction (21.6 mm long, 0.5–2.0 mm thick) could be noted along the bone fragments. At 2 weeks, the regenerate was well structured and filled completely the interfragmentary gap. The growth zone contained numerous bone trabeculae. Periosteal reaction was 24–26 mm long and 2–3 mm thick. The regenerate was larger than the tibia. After about 15 days of fixation (d 48), the regenerate was completely consolidated in all the animals. Cortical bone was reconstructed. Continuity of three or four cortices was reestablished along the regenerate. The growth zone had disappeared. A denser periosteal reaction was noted. After about 30 days of fixation (d 63), the medullary canal was already formed in three out of four dogs. No fracture or deformity occurred after removal of the external fixator because the regenerates

Table 2.1 Duration of lengthening and external fixation

Period	Osteoclasis, ilizarov + FIN	Distraction (lengthening)	External fixation	Removal of external fixator
Date	Day 0	Days 5–33	Days 34–49 = 6 dogs Days 34–63 = 8 dogs	Day 49 = 6 dogs Day 63 = 8 dogs

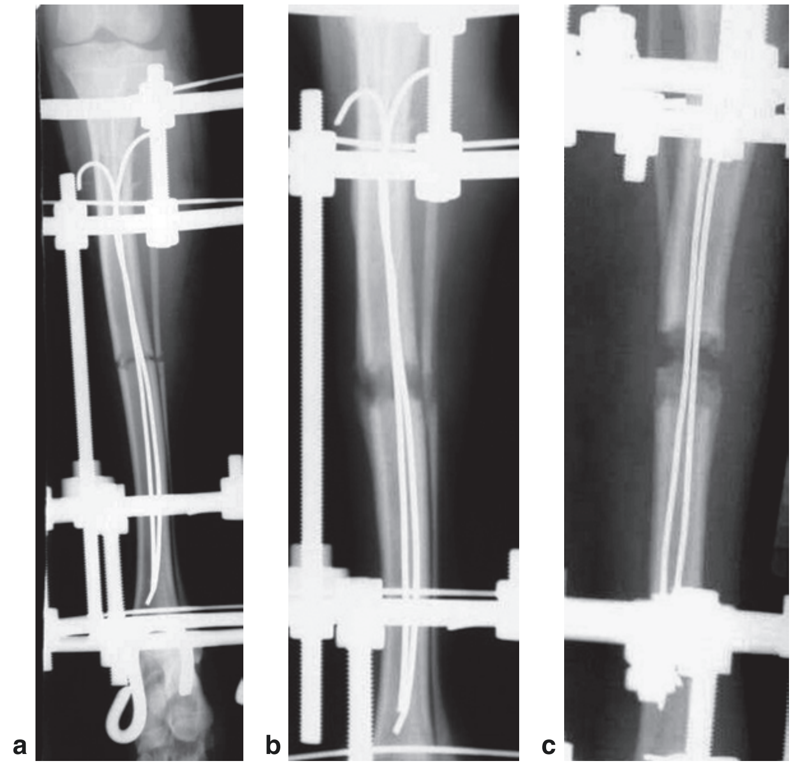


Fig. 2.10 Healing status after 14 days of tibial lengthening (dog) using combined Ilizarov/FIN: (**a**) Ilizarov fixator and two intramedullary nails in place, closed osteoclasis of the tibia; (**b**) X-ray taken after 14 days of lengthening at a rate of 1.75 mm/day; (**c**) X-ray taken after 21 days of lengthening, fracture of the regenerate

had already consolidated, and also because the bones were protected by FIN.

After 15 days of external fixation, histology showed cortical continuity, fully interconnected cancellous trabeculae, and disappearance of the fibrous layer surrounding the new bone (Fig. 2.11a). As a matter of fact, consolidation took place during the fixation period and lasted 2 weeks.

Thirty days after removal of the external fixator, the cortices were thicker. Remodeling of the medullary canal was under way. We were happy to note extensive tissue regeneration along the intramedullary nail (Fig. 2.11b).

This structure can be compared to a stainless steel lead pencil.

Arteriographies performed at the initiation of lengthening, after 6 days of external fixation, and immediately after removal of the intramedullary nails (Figs. 2.12a and 2.12b), showed that the medullary artery had remained patent all the time.

Lastly, no implant migration or skin problems occurred. We found that proper nail contouring ensured stability of bone fragments during lengthening.

2.2.3 Discussion

The Ilizarov lengthening method has revolutionized the biology of bone and bone growth. Preservation of bone environment, periosteum, and particularly, the medullary vascularization, respect of the biological rate of bone growth, use of automatic high-frequency lengthening, preservation of stability and elasticity (provided by the rings): all this works together to provide good to excellent tissue regeneration [3]. The more stable the lengthening site is, the faster it will heal. Although Ilizarov claimed that bone marrow played a major part in new bone formation, a certain number of works that tried to demonstrate the paramount qualitative role of periosteum in distraction osteogenesis have been published [4, 5].

FIN has a proven track record of over 25 years of effective treatment of fractures in childhood based on animal experimentation [1] and above all, on the outstanding experience of the Department of Pediatric Orthopedics, Clinique Chirurgicale, Nancy (France). According to these works, FIN provides a strong elastic frame that enhances the biological effect of redistribution

Fig. 2.11 Histologic sections (tibia – dog): (**a**) specimen at d 49 (fixator removed), cortices were present along the regenerate and continuity was re-established. Growth zone was no longer visible; (**b**) specimen at d 88, 25 days after removal of the external fixator, intramedullary nails were removed just before sacrifice. Regenerate consisted of cortical and cancellous bone tissue. The medullary canal was patent. Ossification was present along the intramedullary nails

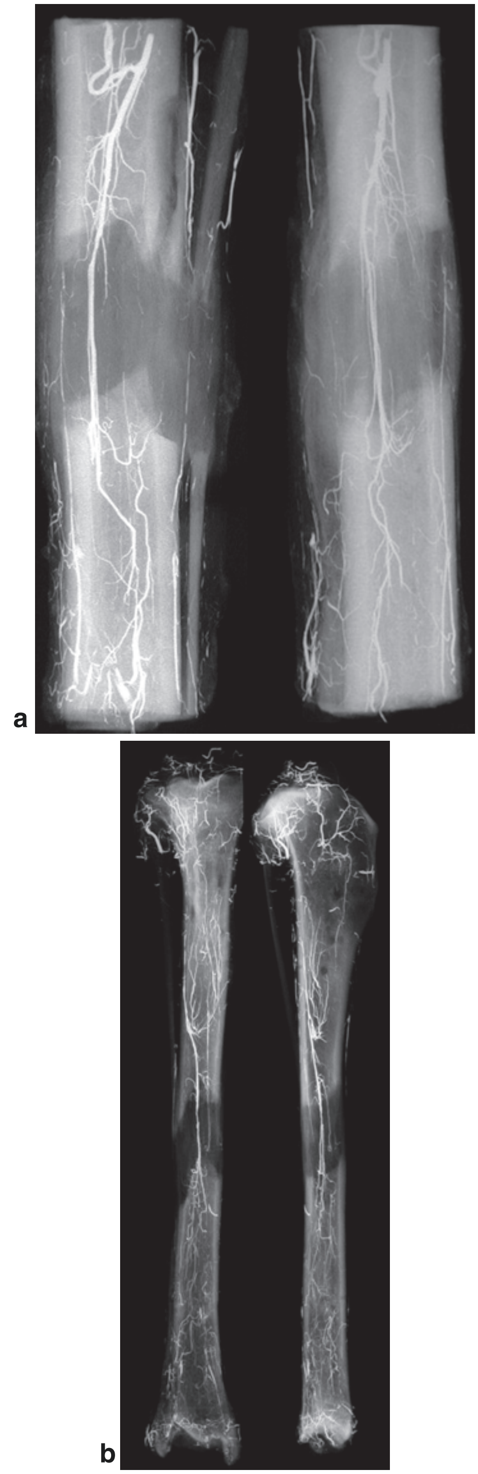


Fig. 2.12 Arteriography: the medullary artery was patent (tibia – dog). (**a**) Arteriography (AP and lateral) of specimen after removal of the intramedullary nails on the 6th day of the fixation period (d 39); (**b**) arteriography (AP and lateral) after 30 days of fixation (d 63)

of blood flow to the periosteal structures through cortical canals, thus stimulating formation of periosteal callus. FIN is a semi-rigid elastic nailing system, which allows for cyclic micro-scale plastic deformation that is most beneficial to healing. Additionally, as the two intramedullary nails do not completely fill the medullary cavity, endosteal callus formation is not inhibited.

We had the idea to combine both elastic systems, Ilizarov and FIN, for limb lengthening [6]. Our animal experiments prove that contoured intramedullary nails do not inhibit endosteal bone formation. On the contrary, despite partial destruction of the bone marrow, the preserved intramedullary circulation stimulates tissue regeneration to such an extent that it becomes necessary to increase the distraction speed to avoid premature consolidation of the regenerate during lengthening.

The biological effect of redistribution of intramedullary blood flow to the periosteal structures stimulates formation of periosteal callus, resulting in extensive periosteal reaction, both along the bone fragments and at the diastasis. When combined Ilizarov/FIN is used, the periosteal reaction is indicative of active tissue regeneration rather than instability of bone fragments.

FIN provides increased stability at the diastasis by resisting translation motion (essentially) in the plane of the nails. Gradual stretching or sliding of the intramedullary nails through the regenerate during lengthening likely enhances the regeneration process. However, the mechanism of biological stimulation of endosteal bone formation remains unexplained. Controlled bone marrow irritation by an intramedullary nail is known to produce localized new bone formation [1]. This has been confirmed in animals, where intramedullary nails positioned at the periphery of the regenerate and gradually pulled have shown to accelerate the formation of new bone [7].

2.2.4 Conclusion

FIN can be used conjointly with external fixation for bone lengthening. Combined use of these two methods allows to stimulate both endosteal and periosteal bone formation. FIN improves stability of the bone fragments at the diastasis, and does not inhibit intramedullary circulation. In bone lengthening, FIN is the only internal fixation method that provides the same optimal conditions for bone regeneration as the Ilizarov method. This is why combined Ilizarov/FIN yields such a good outcome. The results of this experimental study have been, in our department at Kurgan, a determining factor for the use of combined Ilizarov/ FIN method in bone lengthening and correction of bone deformities in patients with limb length discrepancy (LLD) and skeletal pathologies such as familial hypophosphatemic rickets.

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Biomechanics of FIN

3

Jean-Noël Ligier

Before describing the biomechanical features of flexible intramedullary nailing (FIN), it seems important to provide an overview of pediatric biomechanics and its implications in the mechanism of fracture healing.

3.1 Pediatric Biomechanics

A child's bone, whether diaphyseal, metaphyseal, or epiphyseal, differs from adult bone in many ways:

- It is more porous (areolar tissue), it has a lower mineral content (softer), and is therefore, not as strong as that of an adult.
- On the other hand, owing to its higher water content, it exhibits greater plasticity and elasticity.
- It has a thicker periosteum, well vascularized.

These three features typical of pediatric bone demonstrate that there is the same difference (relatively speaking) between pediatric bone and adult bone as between green wood and dry wood.

Based on the analogy between bone and wood, one can easily picture what occurs in bone. As a matter of fact, if a critical bending force is manually applied to a wooden stick:

- Dry wood breaks, and a large amount of energy is quickly released in an audible, palpable, and visible manner: audible "pop," severe jolt in the hands, and significant displacement of the stick ends, which are violently brought together.
- In contrast, green wood breaks gradually. The stick breaks with a dull sound after application of a more or less severe bending load, first in the convexity and then in the concavity of the curve. Energy is slowly released and displacement is limited.

Owing to these specific bone features, four types of fractures are typically seen in children:

- A buckle fracture (or torus fracture) occurs due to axial compression of bone at the metaphyseal-diaphyseal junction.
- A bowing fracture is when the diaphysis appears to be bent without any fracture line evident.
- The well-named greenstick fracture occurs when a bone is angulated beyond the limits of plastic deformity: fracture involving only the convex side of the cortex and its periosteum.
- Hairline fracture (often spiral shaped) with no displacement within its periosteal sleeve.

In addition to these configurations unique to pediatrics, there are several types of fractures, which are also commonly seen in adults:

- Spiral fracture resulting from a rotational injury.
- Transverse fracture produced by pure bending.
- Oblique fracture often produced by combined axial compression and bending.
- Transverse/oblique fracture with or without butterfly fragment.
- Comminuted fracture, rather unusual in children due to the large amount of energy absorbed prior to fracture.

3.2 Biomechanics of Fracture Healing in Children

Healing process is exactly the same as in adult bone.

P. Lascombes, *Flexible Intramedullary Nailing in Children*,
DOI: 10.1007/978-3-642-03031-4_3, © Springer-Verlag Berlin Heidelberg 2010

3.2.1 Diaphyseal Fractures

- During the initial trauma, bone fractures, some blood vessels are ruptured, and the adjacent soft tissue is torn.
- Fracture hematoma results from bleeding of bone and soft tissue. According to some authors [1–3], it is an important determining factor for healing. For others, it does not have an active role [4]; this is based on the finding that near normal healing can be achieved in hemophilic patients, and in patients who have undergone open internal fixation.
- During the early acute inflammatory phase, histamine and other chemical mediators are released, which aggravates the initial devitalization of bone and soft tissue.
- Formation of external or periosteal callus actually initiates the repair process by forming encircling collars of callus at both ends of bone fragments, in the living bone area. These wedge-shaped collars gradually approach each other until they meet, and union is established in a few weeks. This primary callus response described by McKibbin [1] is inhibited by rigid fixation and promoted by micromotions at the fracture site. The collar cells differentiate into osteoblasts or chondrocytes, depending on their vascular environment. External callus is the predominant callus, which forms most rapidly, on the condition that periosteum is present [3].
- Internal or endosteal callus originates from the hematoma in the medullary cavity, and forms from the cells of the osteogenic layer of the endosteum. It seems to be a slow process of secondary importance that is assisted by the absence of motion at the fracture site, which eliminates the endochondral phase.
- Callus remodeling begins after dense calcification (of soft callus and hard callus) has occurred. It consists of resorption of the primary bony callus by the osteoclasts and apposition of mature lamellar bone by the osteoblasts. Lamellar bone trabeculae are arranged along the lines of mechanical stresses. In children, this remodeling process is further enhanced in case of angular deformity by appositional growth of bone, especially, as the growth zone is active and close to the fracture site.
- Primary bone healing, as described by authors from the Swiss Association for Osteosynthesis (AO) [5], is a different process: it is achieved with artificial methods of mechanical compression of the fracture fragments and requires very rigid fixation.

3.2.2 Metaphyseal Fractures

The metaphysis acts as a damper between the epiphysis and the diaphysis. It is vulnerable to compressive forces (mainly).

The fracture surface is generally wider, more bleeding, and has a more transverse orientation in the metaphysis than in the diaphysis. As a result, it is more stable after reduction; actually, internal fixation is just this “little something” that protects against secondary displacement.

Furthermore, the metaphysis is richly vascularized so that after the acute inflammatory phase, healing can rapidly take place through “creeping substitution.”

Lastly, due to the close proximity of the growth zone, slightly imperfect reductions remodel into perfect alignment. Remodeling is even better in young children with active epiphysis. Therefore, in a 10-year-old child with a fractured humerus, it is more important to achieve optimal alignment of a supracondylar fracture than of a surgical neck fracture.

3.2.3 Conclusion

Based on the above-mentioned factors, clearly, pediatric fractures heal faster than adult fractures, even though healing mechanisms are identical:

- As the energy of the trauma is released slowly, damage to bone and soft tissue is less severe.
- Periosteum is thicker with a better vascular supply: fractures tend to be more stable with less displacement than in adults, and formation of external callus is enhanced.
- Bone remodeling is promoted by active growth zones.
- On the other hand, healing of the overgrowth that follows bone fractures in children results in lengthening of the fractured bone.

3.3 Biomechanics of FIN

3.3.1 Goals

3.3.1.1 Primary Goal

The primary goal of FIN is the same as that of rigid fixation: rapid restoration of function. However, there is one major difference: with FIN, restoration of function is due to rapid bone healing through optimal development of the periosteal callus, whereas with rigid fixation, is due to the artificial stiffness provided by the device.

It is important to stress the difference between rigid and elastic internal fixation:

- Rigid internal fixation: due to the rigidity of the constuct that is critical to "primary bone union" and "cortical callus" formation, no external callus can develop because response is abolished altogether. The appearance of external callus is even considered as evidence of technical failure [5].
- Elastic internal fixation: contrary to rigid fixation, elastic fixation needs some degree of relative movement to promote formation of the external callus, which is the physiological callus that forms most rapidly, and has the highest biomechanical strength.

Interestingly, 1 μ displacements can prevent the formation of cortical callus, whereas displacements, one thousand times greater (i.e., of the order of 1 mm), promote the formation of external callus.

3.3.1.2 Secondary Goals

Secondary goals of FIN include:

- Eliminate, if possible, the risks (i.e., deep infection or nonunion) associated with traditional operative treatments.
- Avoid the conspicuous scars that are inevitable with open surgery, and even the risks of blood transfusion.
- Minimize the overgrowth that follows pediatric bone fractures by quickly restoring the patient to normal function, which is possible since their is no need for additional immobilization, and the healing period is very short.

3.3.2 Basic Principles

FIN uses three basic principles to promote optimal development of external callus.

3.3.2.1 Tissue Preservation

FIN relies on bone and soft tissue to stabilize the intramedullary construct [6–10] and promote fracture healing. Therefore, the remaining living tissues at the fracture site are necessarily preserved.

Closed internal fixation avoids further muscle weakening and periosteal damage. It also offers the advantage of preserving the fracture hematoma and its osteogenic potential suspected by McKibbin [1] and evidenced by Mizuno [2].

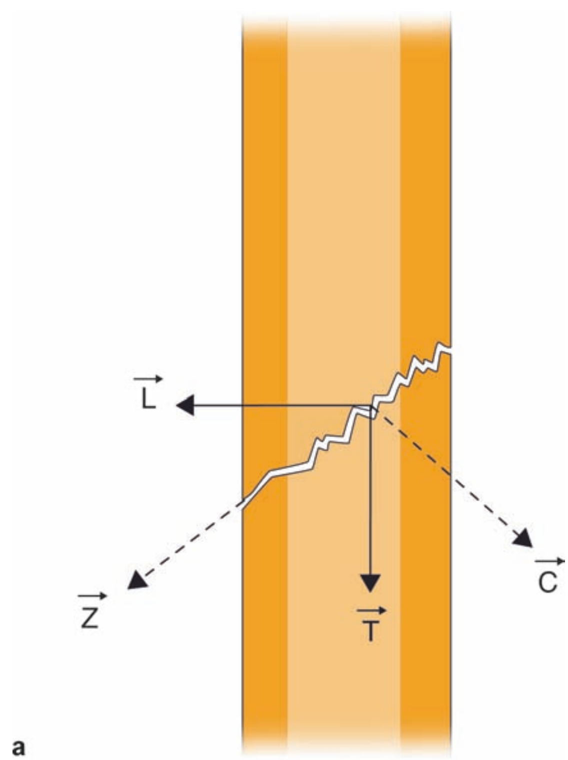

Fig. 3.1 Distribution of forces according to the type of fracture and the type of construct. (**a**) Directions of axial forces (*T* force generated by muscle tone, that resolves into a compression component *C* and a shearing component *Z*. A force *L* is generated that produces lateral displacement

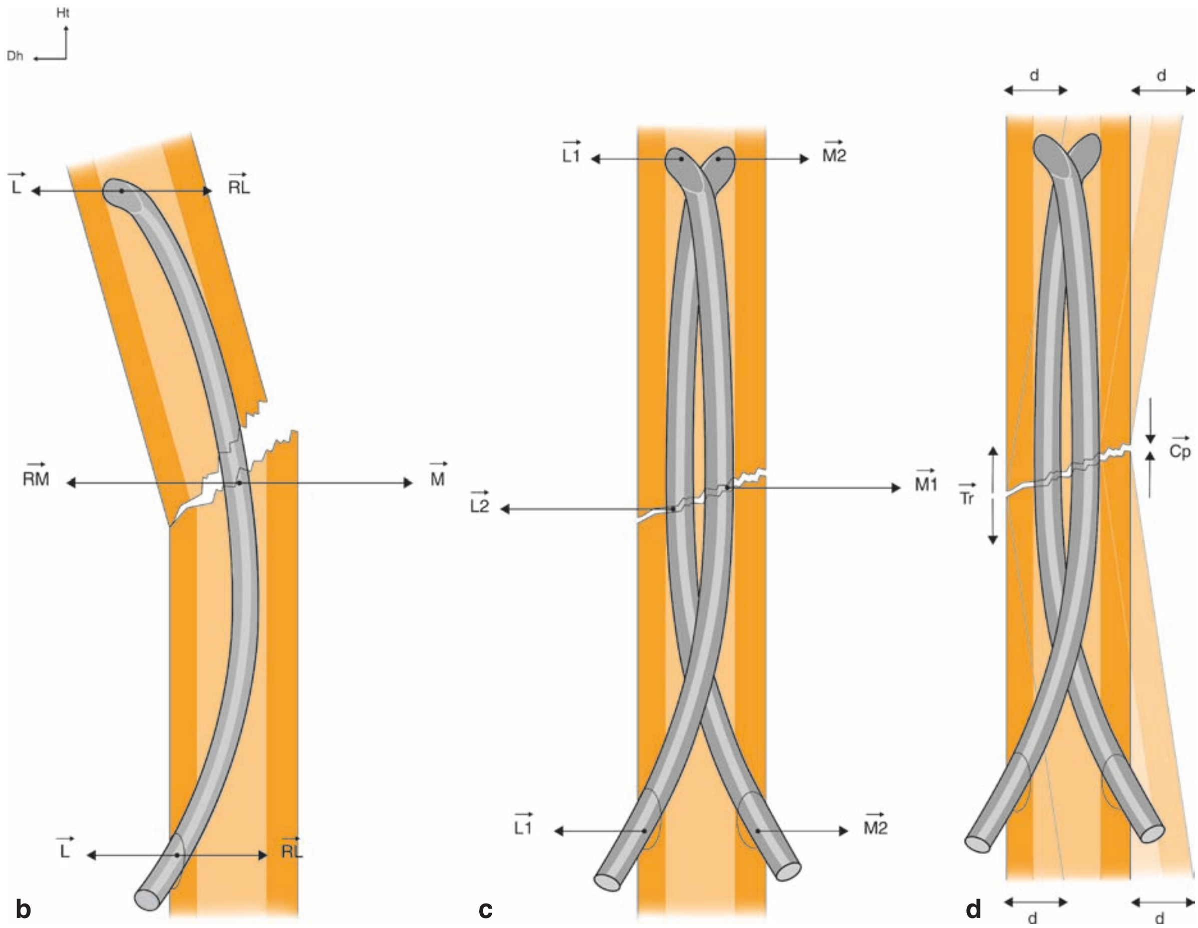

Fig. 3.1 (*cont.*) (**b**) Equilibrium status with valgus angulation after insertion of the lateral nail. (**c**) The second nail is in place: realignment produced by the two opposing curves; (**d**) following a slight displacement of the fracture, the nails return to their initial position of equilibrium owing to their intrinsic elasticity. Compression-distraction forces (compression on the concave side, traction on the convex side) act alternately at the fracture site

On the other hand, FIN is likely aggressive to the medullary vessels but not to a dramatic degree, as demonstrated by Popkov (Chap. 2). For instance, it does not seem to adversely affect healing by external callus. In addition, free motion of the nails is maintained in the medullary canal, which explains the lower susceptibility to infection as compared to the traditional intramedullary nails, which inevitably destroy the medullary vascularization by creating a poorly vascularized gap at the metal-bone interface and inside the IM locked nail itself.

Viability of the periosteum is critically important to the repair process: where periosteum has been destroyed, no external callus can develop, as can be seen in some high-energy open fractures. One must not aggravate severe initial damage with open surgery or periosteal stripping.

3.3.2.2 Elimination of Deleterious Stresses

Study of fracture healing showed that a callus bridge consisting of longitudinally oriented cells forms between the fragments [1], and that a certain degree of movement is necessary for optimal development of the external callus.

The best way to promote development of the external callus is to allow for movements that assist in building the bridging callus, and eliminate those which may break this bridge. Compression-traction stimuli are known to promote the formation of external callus, whereas torsional and shearing stimuli have a deleterious effect [7].

In diaphyseal fractures, a perfect FIN construct consisting of two intramedullary nails with opposing curves can convert negative stimuli to positive ones (Fig. 3.1):

- Let's consider an oblique fracture (a): the axial force T generated by the muscle tone and the soft tissue resolves into an interfragmentary compression component C, and a shearing component Z, which is detrimental to healing because its lateral component L produces lateral displacement at the fracture site.
- The contoured nail (b) has a three-point contact with the bone. It produces forces, which tend to cause angulation of the fracture site. In a reduced fracture, the translation force L is higher than the soft tissue resistance R; this results in angular deviation, which is no more than the equilibrium status between the bending moment of the nail and the resistive strength of the musculoskeletal structures. The second contoured nail also has a three-point contact with the bone and balances the first nail with an equal but opposite moment (c). The two nails act complimentarily to stabilize the fracture; thus, shearing forces are neutralized. The only remaining forces are the axial compression forces (Cp) or axial traction forces (Tr), which promote healing (d).

However, achieving a well-balanced construct is a little more complex:

- Significant contouring is necessary to provide the nail with an adequate elastic restoring force when subjected to angulation forces: the angle of curvature must be greater than the actual curvature of the nail in the medullary canal.
- In a construct with two opposing curves, both nails must have identical curves, and the entry holes must be symmetrically located on the bone (whenever possible) so as to avoid angular deviation.
- Three-point contact with the bone is standard: the preferred anchoring site is the metaphysis opposite the entry hole, where dense cancellous bone provides the best stability in all three planes. The entry site has always less axial and rotatory stability. The main technical difficulty lies in accurate positioning of the apexes of the curves at the fracture site where the spread should be greatest; this sometimes requires additional contouring locally.

Both-bone forearm fracture is a special case. One single intramedullary nail in each bone is sufficient: the two nails and the adjacent joints make up a strong frame-like construct [9]. However, as usual, both nails are initially contoured to the same shape, and are positioned so that their respective concavities face each other.

As metaphyseal fractures are intrinsically more stable, unipolar nailing is perfectly suitable provided that the nails are divergent at the fracture site. In radial neck fractures, one single nail is used. In some metaphyseal fractures, the nail can also assist in reduction.

3.3.2.3 Stability and Role of Soft Tissues

Soft tissues, and particularly, tendons and ligaments play three major roles in FIN.

Rotatory Stability

Owing to their oblique position relative to the fractured bone, muscles and tendons act in the same way as the shrouds that hold the mast up on a sailboat, and they can resist significant angular deviations, as well as rotational malunion [6, 9].

Trophic Role

Muscle contractions, which are enhanced by FIN, play a trophic role by increasing local nutritional supply. This creates an oxygen-rich atmosphere, which promotes production of osteoprogenitor cells, thus eliminating the chondroblast stage [1].

Morphological Role

Muscle contractions also have an influence on the morphology of callus. Normally, the randomly oriented initial callus which arises from the damaged tissues gradually takes on a regular elongated shape. By contrast, poor quality diffuse callus can be found in patients with neurological disorders (i.e. cerebral palsy, spina bifida, traumatic paraplegia etc...) and hypertrophic callus can be found in patients with head trauma.

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4 Stainless Steel or Titanium?

Jean-Michel Clavert, Philippe Gicquel,
and Marie-Christine Giacomelli

4.1 Clinical Performance

Titanium and stainless steel: which of these two materials is best suited for flexible intramedullary nailing (FIN) [1]? The first nails were made of stainless steel, as stainless steel Kirschner wires were available in all diameters, in every operating theater. Later, ashift to the use of titanium occurred on the ground that titanium had better elastic properties, and that elasticity was the single most important factor in the success of this method. Nevertheless, this merits further discussion and analysis. Experience shows that excellent results have been achieved in children less than 10 years old, whatever the implant material used. It is completely different in older children and adolescents, especially if overweight or obese. As a matter of fact, in a certain number of cases, insufficient reduction or secondary displacement seemed to be attributable to excessive elasticity. Secondary displacement tends to occur either when the child wakes up from anesthesia due to recovery of muscle tone, during in-bed mobilization, or on resumption of partial or total weight bearing. In the worst-case scenario, it may cause nail deformation. In an attempt to address this issue, the diameter of the nail (stainless steel and titanium) was increased. But the diameter of the medullary is a self-limitation to the diameter of the nail. The use of the mathematic formula: nail diameter = diameter of the medullary canal divided by 2 less 1 mm ($d=m/2-1$) seems to be the only and best method available to determine the appropriate nail size. Based on this, the question as to which material is best really makes sense, and places adolescents at the heart of the debate because it is in adolescents that residual angulation, malunion, or shortening due to impaction of bone fragments occur. Femoral fractures in adolescents should not be managed with the standard intramedullary nails used in adults due to the high risk of femoral head necrosis. During insertion through the tip of the greater trochanter, straight nails often shift medially and jeopardize the medial circumflex femoral artery, which carries a high risk of necrosis of the femoral head. Considering the severity of this complication and its sequelae, FIN should be preferred in most children in whom physes of the proximal femur are still open.

4.2 Biomechanical Features

Therefore, attention must be directed to the biomechanical features of stainless steel and titanium in terms of resistance to deformation and elastic restoring force after elastic displacement [2, 3, 4, 5].

The primary approach consists of:

- Comparing the modulus of elasticity of stainless steel and titanium.
- Evaluating and comparing the force necessary to produce an elastic deformation in both materials.
- Evaluating and comparing the bending yield load in both materials.

There are several types of stainless steel and titanium alloy. Intramedullary nails are not fabricated from commercially pure (CP) titanium but from titanium alloys of varying composition. Composition of the stainless steel alloy used for intramedullary nails also varies from one manufacturer to another. These variations in material composition account for the slight discrepancies in the results of mechanical tests, and the differences noted between these two materials are still meaningful. For comparison purposes, we have evaluated the most commonly used materials: stainless steel ISO 5832-11 and titanium ISO 5832-1D.

P. Lascombes, *Flexible Intramedullary Nailing in Children*,
DOI: 10.1007/978-3-642-03031-4_4, © Springer-Verlag Berlin Heidelberg 2010

4.2.1 Evaluation of Elastic Modulus

The ratio of tensile stress to tensile strain (i.e., the stress applied to a body to the strain that results in the body in response to it) remains constant as long as the deformation produced is mild and the yield point has not been reached. This constant is called the Young's modulus (E), which is expressed, in N/m^2 or in pascals.

Young's modulus E = σε where:

- σ = F/Ao (force/cross-sectional area – pascals).
- ε = ΔL/lo (change in length/original length – no unit).

Young's modulus for each material:

- Stainless steel (Iso 5832-11): 200 GPa.
- Titanium (Iso 5832-1D): 110 GPa.

The elastic modulus of titanium is lower than that of stainless steel: its elasticity is about twice that of stainless steel.

4.2.2 Elastic Deformation

The three-point test used for measurement of elasticity is illustrated in Fig. 4.1. It allows measuring the deformation produced by a given force F applied to a stainless steel and a titanium nail. Testing was performed at the GEBOAS (Groupe d'Etude Biomécanique Ostéoarticulaire de Strasbourg) Laboratory. Behavior of stainless steel and titanium nails (currently available on the market) of various diameters is shown in Fig. 4.2 (load-deformation curves).

This study confirmed the lower elasticity (sharper slope), and therefore, the higher stiffness of stainless steel as compared to titanium.

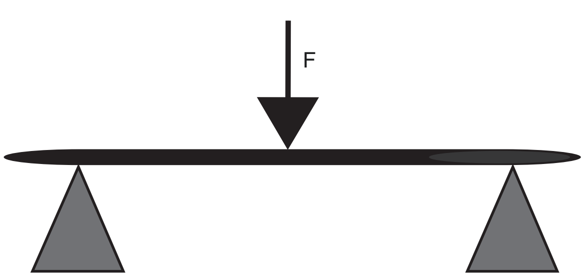

Fig. 4.1 Schematic of a three-point test set-up

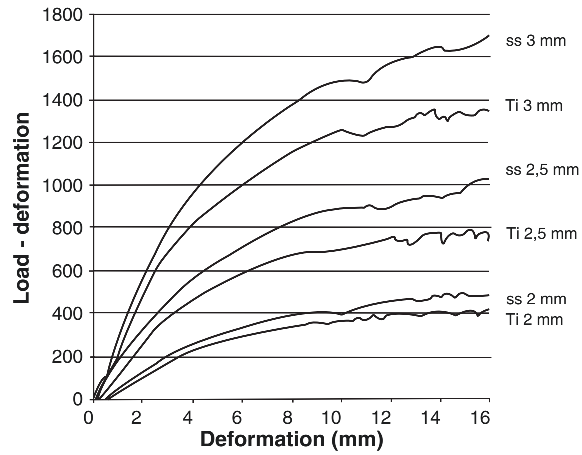

Fig. 4.2 Load-deformation curves for commercially available stainless steel (ss) and titanium (ti) nails of different diameters

Bending stiffness is proportional to the elastic modulus and to the fourth power of diameter. Computed values are presented to Table 4.1 (Bending stiffness = Ex.I where E = Young's modulus (N/mm^2) and I = moment of inertia (mm^4)).

Results show that, for the same diameter, a stainless steel nail has a bending stiffness almost twice as high as that of a titanium nail.

For diameters greater than 2.5 mm, a stainless steel nail has a bending stiffness similar to that of 0.5 mm larger titanium nail. It is clearly shown in Table 4.1: a 3.0 mm diameter stainless steel nail has a bending stiffness of 795 N/mm, almost equal to that of 3.5 mm diameter titanium nail (810 N/mm).

When contoured nails are inserted into the medullary canal, an elastic restoring force is applied to the cortex at the three contact points (Fig. 4.3), a force that reduces the fracture at the apex of the curve. It is interesting to note that for two nails with the same angle of curvature and diameter, the elastic restoring force of stainless steel (F in Fig. 4.3) is twice as high as that of titanium. If it is less of a concern in a young child, it is

Table 4.1 Bending stiffness of stainless steel vs. titanium nails

Diameter (mm)	Titanium (N/mm^2)	Stainless steel (N/mm^2)
1.5	27	46
2.0	86	157
2.5	211	384
3.0	437	795
3.5	810	1474
4.0	1382	2515

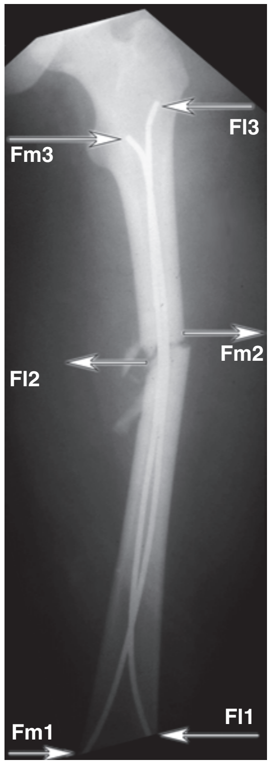

Fig. 4.3 Elastic restoring forces. Forces Fm are for the medial nail. Forces Fl are for the lateral nail. Each nail has three contact points: entry point, apex of the curve where the nail makes contact with the cortex, and anchoring point. This example shows titanium nails of a very small diameter – but the medullary canal would not accommodate bigger nails. Elastic restoring force of the lateral nail is insufficient to obtain complete reduction of the fracture

critically important in an overweight adolescent. It also explains why, in such patients, better reduction is achieved with stainless steel nails, and/whereas elastic axial deviations may occur with titanium nails.

4.2.3 Bending Yield Load

Bending yield load is the load that causes failure under bending (Fig. 4.4). Values are presented in Table 4.2.

For the same nail diameter, the risk of failure is much lower with stainless steel than with titanium. Admittedly, implant breakage is exceptional with FIN, and deformation is rare, except if the patient sustains a new trauma. However, a comparative study of bending yield loads showed a not inconsiderable difference between stainless steel and titanium.

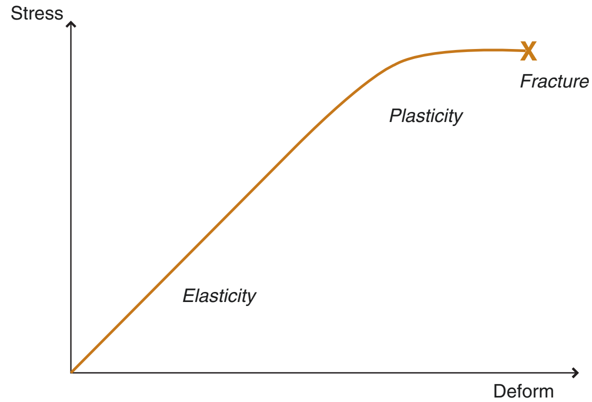

Fig. 4.4 Yield point on a load-deformation curve

Table 4.2 Bending yield load

Diameter	Stainless steel (Mpa)	Titanium (MPa)
1.5	2907	2158
2.0	2866	2150
2.5	2923	2192
3.0	3083	2289
3.5	3082	2311
4.0	3275	2456

4.3 Practical Applications

Based on these mechanical data, it can be concluded that stainless steel is a much better choice for adolescents often involved in intense activities [6]. For an equal diameter, its elasticity is lower than that of titanium, and its elastic restoring force is twice higher. Furthermore, it has a higher bending stiffness: we have seen that the bending stiffness of a stainless steel nail is equal to that of 0.5 mm larger titanium nail.

Therefore, one can say that both stainless steel and titanium are suitable for children, whereas stainless steel is definitely the best choice in adolescents. Besides, in terms of cost-effectiveness, stainless steel will obviously be more attractive to the hospital's financial services department.

4.4 Complications Associated with the Use of Stainless Steel Nails

In clinical practice, comminution at the fracture site (third fragment) during nail crossing and nail rotation is more often reported with stainless steel nails than with titanium nails, which is easily understandable since a stiff stainless steel nail applies more pressure on the cortex. Rotation of the nails generates even higher forces, which explains the higher incidence of comminution at the fracture site (third fragment), even where the preexisting fracture line was hardly, if at all, visible on preoperative X-rays.

Another complication frequently associated with stainless steel is winding of the second nail around the first one during insertion. The final pattern is not that of two nails with opposing curves: it looks like the intertwined caduceus of physicians (Fig. 4.5). Such an awkward construct cannot be expected to perform like a standard one. Again, this is due to the bending stiffness of the material: in a narrow space, a stainless steel nail readily winds around the other one when rotated clockwise or counter clockwise.

Fig. 4.5 Medial nail winding around the lateral nail. Cast immobilization was necessary because the child had a fracture of the contra lateral femoral neck

4.5 Corrosion

After removal of the nails, fretting corrosion is noticeable with the naked eye at nail intersection. The friction area has a dull surface appearance and microstructural changes are observed. Corrosion is confirmed by optical or electronic microscopy. It occurs with both stainless steel and titanium. It is a common phenomenon in screw plates, and it is even more severe in the presence of micromotions at the metal-metal interface. It is exactly what occurs in FIN during the healing period. This suggests that microscopic metal particles are generated and disseminated in the body. It is the reason why early nail removal (i.e., about 4 months after injury) is advocated.

4.6 Conclusion

In a child aged less than 10 years, stainless steel and titanium nails yield similar results. In adolescents, especially if obese, where the nails are subjected to critical dynamic stresses, stainless steel offers greater stiffness than titanium, and its elastic restoring force is twice higher than that of titanium. A stainless steel nail is equivalent to a titanium nail that is 0.5 mm larger, which is not negligible.

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5 Surgical Technique: Basic Principles

Pierre Lascombes and Jean-Damien Métaizeau

The flexible intramedullary nailing (FIN) technique is based on well-established biomechanical principles. It is used for internal fixation of long bone shaft fractures in children and adolescents. Success of the procedure relies heavily on the quality of the surgical technique and therefore on the surgeon's skill and experience. Thorough understanding and familiarity with this three-dimensional technique are mandatory to launch into a FIN procedure. This technique is also perfectly suited for a number of metaphyseal fractures, in which, however, the biomechanical principles of stabilization differ from those used in diaphyseal fractures.

5.1 Appropriate Constructs

5.1.1 Diaphyseal Fractures (Humerus, Forearm, Femur, Tibia)

Ideally, at the end of the procedure, one should have two nails with opposing curves. The concavities should face each other, and the apexes of the curves should be located at the fracture site. Thus, both nails cross each other proximal and distal to the fracture. This can be performed using an *antegrade* technique: both nails inserted through the proximal metaphysis and directed toward the distal metaphysis, or using a *retrograde* (ascending) technique through the distal metaphysis. In certain situations, it may be desirable to perform a *combined antegrade/retrograde* FIN (Fig. 5.1).

The second most important factor in achieving a perfect construct is the number of incisions needed to properly position the nails and facilitate insertion. Again, an ideal, well-balanced construct should use two nails (*bipolar* construct) inserted through two metaphyseal incisions (one medial, one lateral). However, depending on the position of the bone relative to the skin surface and on the adjacent neurovascular structures, two percutaneous approaches may not be possible, and may even be hazardous. In such cases, one single incision is made in a safe area for both nails. It is recommended to create two distinct entry holes (one for each nail), one above the other (not side-by-side) to avoid weakening of the bone and minimize the potential for secondary fracture. This procedure is called *unipolar* FIN. The first nail follows a direct route, with its concavity and leading end turned toward the entry hole side. The second nail must be rotated 180° as soon as it enters the medullary canal, so that its concavity and leading end are turned opposite to the first nail (Fig. 5.2).

Basically, the more distant the fracture is from the entry holes, the easier it is to achieve a perfect construct. But two additional factors are to be considered: easy access to the affected bone, and perfect balance of the opposing curves.

This explains why the vast majority of femoral fractures are managed with bipolar retrograde FIN (Fig. 5.1c), whereas distal femoral fractures are best managed with unipolar antegrade FIN using a subtrochanteric approach [1] (Fig. 5.2a). Most tibial fractures are managed with bipolar antegrade FIN (Fig. 5.1a); bipolar retrograde FIN should be reserved for some fractures of the proximal one-fourth of the tibia (Fig. 5.1b). Humeral fractures are preferably treated by unipolar retrograde FIN, using a lateral supra-epicondylar approach (Fig. 5.2b), although some authors use a bipolar FIN with a medial and a lateral nail [2]. As regards both-bone forearm fractures, a combined antegrade (ulnar)/ retrograde (radial) FIN with one nail in each bone is unquestionably the easiest method (Fig. 5.2c), although some surgeons suggested

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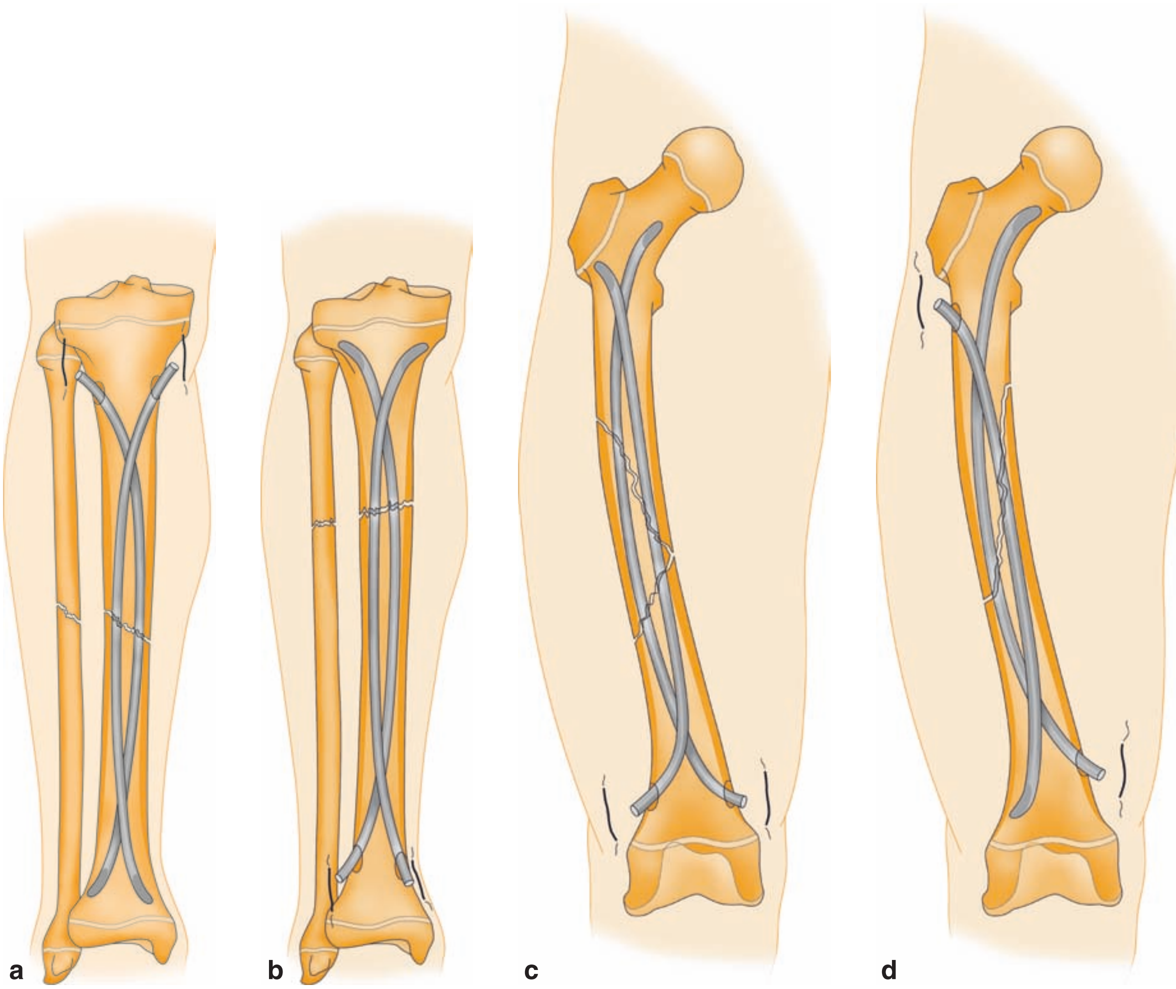

Fig. 5.1 Bipolar flexible intramedullary nailing (FIN). (**a**) Tibial bipolar antegrade FIN; (**b**) tibial bipolar retrograde FIN; (**c**) femoral bipolar retrograde FIN; (**d**) femoral bipolar antegrade/retrograde FIN

the use of a "reversed" FIN, which, however, is much more technically demanding [3]. The methods we are recommending have the advantage of being simple and reproducible, but of course, each surgeon is free to use the method he/she is most familiar with.

5.1.2 Metaphyseal Fractures

In metaphyseal fractures, the biomechanical principle is totally different. The opposite bending moments created by the two nails are not the essential feature; what matters are the divergent directions of the nails in the epiphyseal-metaphyseal region. Extent of the diaphyseal support provided by the nails is an important factor in influencing the stability of the fixation.

Using the same rationale as for diaphyseal fractures, several constructs are suitable:

- Fractures of the proximal humerus (epiphyseal separations and metaphyseal fractures) are amenable to unipolar retrograde FIN using the same technique as in humeral shaft fractures (Fig. 5.3a).
- Supracondylar humeral fractures are treated by unipolar antegrade FIN through a lateral incision in the mid-shaft of the humerus (Fig. 5.3b).
- Radial neck fractures are treated by unipolar retrograde FIN from a radial approach (Fig. 5.3c).

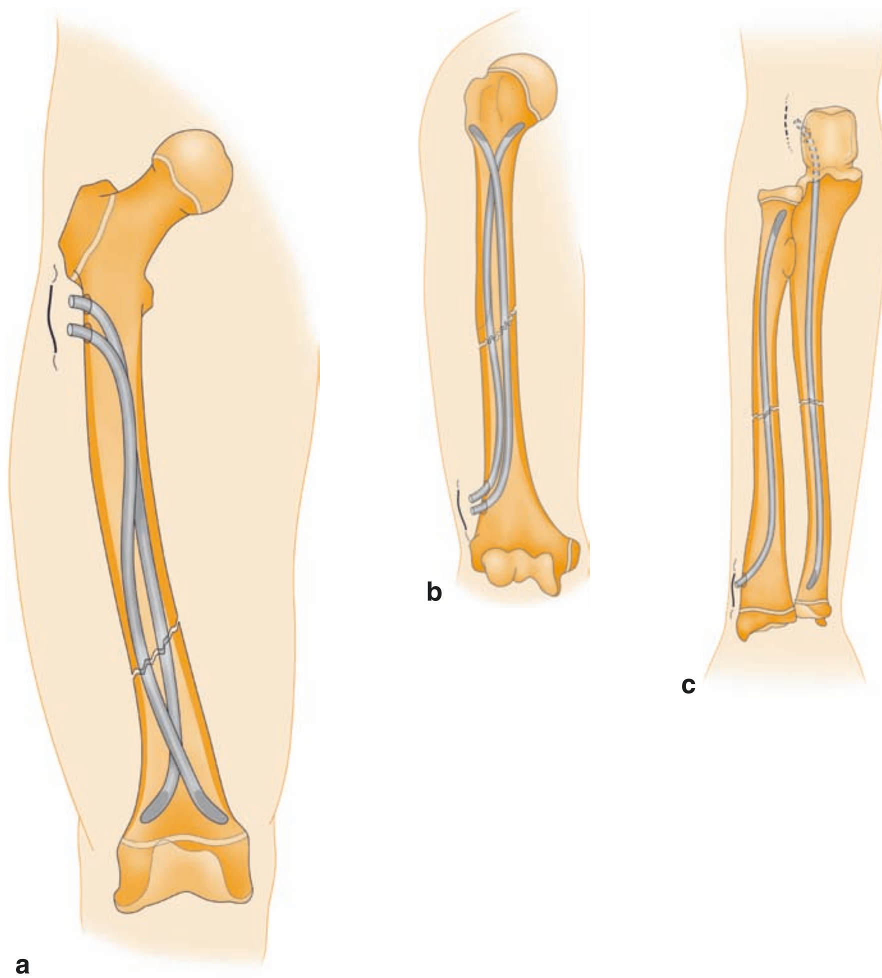

Fig. 5.2 Unipolar diaphyseal FIN. (**a**) Femoral unipolar antegrade FIN; (**b**) humeral unipolar retrograde FIN; (**c**) forearm antegrade/retrograde FIN: retrograde for radius, antegrade for ulna

5.2 Implant Selection

5.2.1 Materials

The nails used have a diameter less than or equal to 4.0 mm. Their most important property is their intrinsic elasticity. As a matter of fact, X-rays show the final shape of the nails in situ, but what is important is the bending moment that is created in the bone and that will maintain reduction. The metal with the lowest elastic modulus is Ti6Al4V. Elastic modulus of this titanium alloy is much lower than that of stainless steel [4, 5]. Excellent results can be achieved with stainless steel nails, indeed, but how could we forget those cases where stainless steel nails became entangled and were impossible to control (Figs. 1.3 and 14.11). Ti6Al4V is actually the right choice, as some of the currently available alloys do not meet the elasticity requirements of FIN. But, it is up to the surgeon to decide whether titanium or stainless steel nails should be used according to the fracture type (see Chap. 4).

5.2.2 Nail Diameter

5.2.2.1 Lower Extremities

If one were to define a mathematic formula for nail diameter, it would be: nail diameter = 0.4 × diameter of

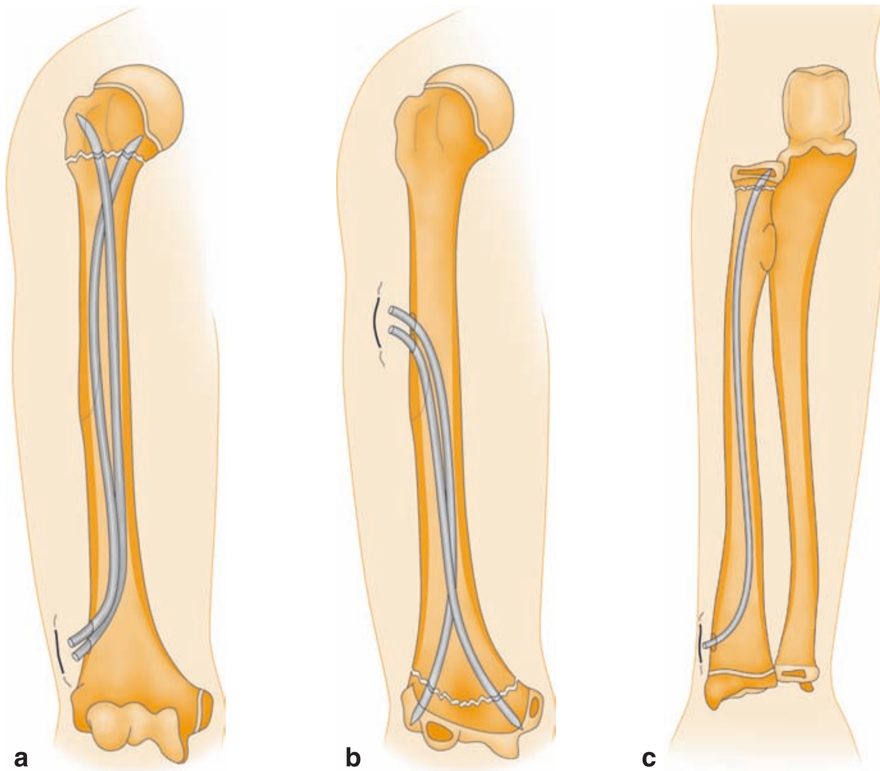

Fig. 5.3 Metaphyseal FIN. (**a**) Unipolar retrograde FIN of the proximal humerus; (**b**) unipolar antegrade FIN of the distal humerus; (**c**) unipolar retrograde FIN of the proximal radius

the medullary canal ($d = 0.4 \times m$), as the diameter of the nail must be *at least* 40% of that of the medullary canal. Another formula may be used: nail diameter > diameter of the medullary canal divided by 2 less 1 mm ($d = m/2-1$). Minor adjustments to fit specific cases are acceptable, but experience shows that in case of doubt, the next larger diameter should be selected. A smaller nail might not be strong enough and would suffer plastic deformation (Fig. 5.4).

5.2.2.2 Upper Extremities

For the upper extremities, in particular the humerus, a nail diameter, which is 33% of the intrameduallary canal diameter, suffices. It is rare to utilize a nail bigger than 3.0 mm for the humerus. For the radius and the ulna, the 40% FIN rule of thumb for nail diameter choice in the lower extremities is appropriate. Occasionally, the nail diameter may reach 50% of the medullary canal. However, it is seldom necessary to use a nail bigger than 2.5 mm for the radius or the ulna.

5.2.3 Nail Length

Most of the currently available implants require some trimming prior to wound closure. But sectioned ends may cause subcutaneous and cutaneous lesions. For this reason, some surgeons use protective end caps, which have two major disadvantages: (1) some tend to slip off, (2) nail prominence is worse due to the volume of the cap. To address this issue, screw-in plugs have been developed, but they result in enlargement of the entry holes, which causes bone weakening once the nails are removed.

The other option is to use fixed-length nails with an atraumatic bullet tip. The appropriate length is determined by measuring the contralateral bone, and is (at the most) equal to the distance from the proximal physis (greater trochanter for the femur) to the distal physis. Furthermore, its end facilitates removal. However, there are a few drawbacks, the main one being increased inventory and additional cost for the hospital/clinic. Secondly, the last step of the procedure is trickier

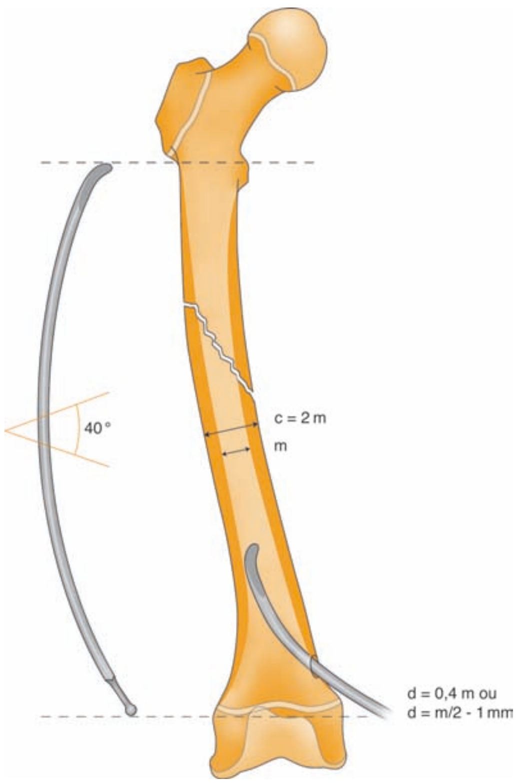

Fig. 5.4 Nail diameter: $d = 0,4 \times m$ or $d = m/2\text{-}1$

because the nail cannot be rotated before final impaction. Lastly, the appropriate length must be determined with accuracy (Fig. 5.4).

Therefore, it is much preferable to properly cut the nail with an appropriate cutter that will provide a clean cut (as with a guillotine) and will not crush the nail end.

5.2.4 Nails with a Curved Tip and a Tapered End

The prebent nails currently available from the industry often have a suboptimal design. Straight nails can be bent to the desired shape by the surgeon in the operating room. Good understanding of the role of the nail tip and nail tip curve is essential. The curved tip is designed to help direct the nail toward the inner cortex opposite the entry hole, and then facilitate entry into the medullary canal (Figs. 5.5a, b). Radius of the curvature may be slightly increased or decreased, as needed, to match the patient's anatomy.

The length of the curved tip should not exceed the length of the orthogonal projection of the isthmus of the medullary canal, otherwise the nail will get stuck

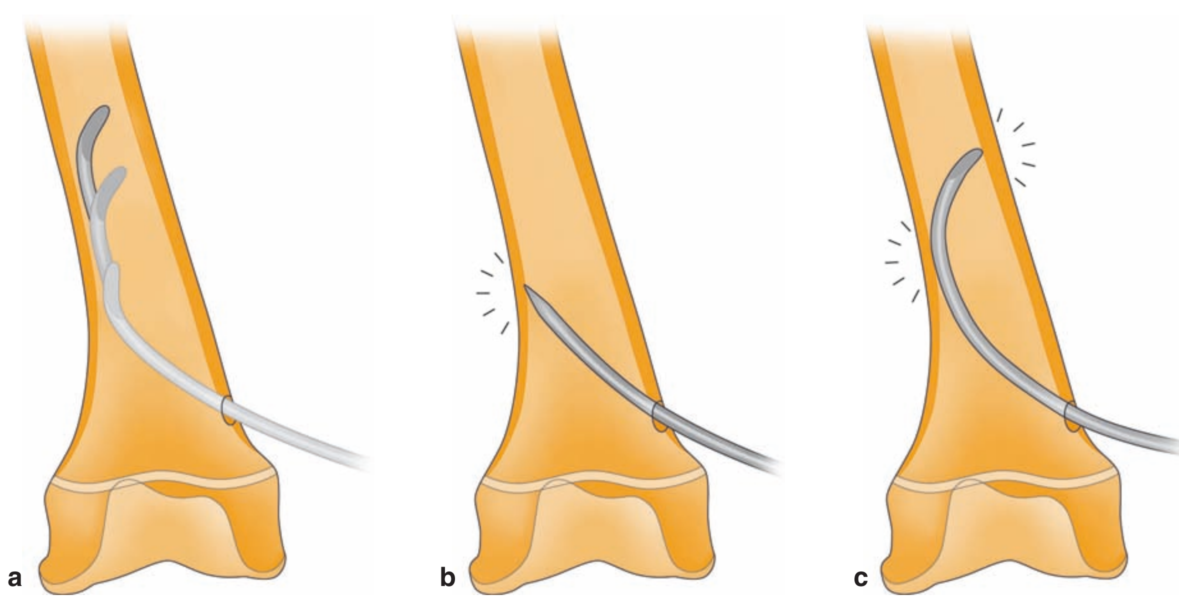

Fig. 5.5 Nail insertion. (**a**) The curved tip of the nail facilitates insertion into the medullary canal; (**b**) a straight sharp nail might penetrate the opposite cortex; (**c**) a curved tip that is too long will get jammed in the medullary canal

in the bone (Fig. 5.5c). In a very narrow canal, it is recommended to slightly trim the curved tip.

The curved tip is effective in preventing jamming in the bone trabeculae opposite the entry hole, and facilitating advancement of the nail within the medullary canal. But, in the dense cancellous bone of the metaphyseal- epiphyseal region, the curved tip blocks nail progression. Forceful advancement using a slotted hammer might result in distraction of the fracture site. This is the reason why nails with a tapered end are advocated to treat metaphyseal fractures.

5.2.5 Nail Contouring

It is during the contouring procedure that the personal skill of a pediatric traumatologist makes the difference. Performing a FIN is not just achieving correct alignment through nailing; the real goal of FIN is to generate corrective forces. To achieve this goal, the apex of the curve must be located at the fracture site. Both concavities face each other and nails intersect proximal and distal to the fracture site. Therefore, the surgeon performs contouring manually. Radius of curvature must be about 50–60 times greater than the diameter of the nail, and location of the bend on the nail depends on the anatomic location of the fracture (Fig. 5.6). Obviously, this is difficult to achieve without appropriate tools; in particular, a template can be most helpful. It is essential to create a nice smooth curve, and not a sequence of more or less aggressive bends performed with inappropriate tools. Hand contouring that is performed by the surgeon is uniform. It is recommended to shape both nails simultaneously to achieve symmetric curves. Any necessary adjustment can be performed intraoperatively, provided that the nail is partially inserted. Thus, the radius of curvature can be gradually decreased as the nail progresses; this is necessary where the fracture line is close to the entry site.

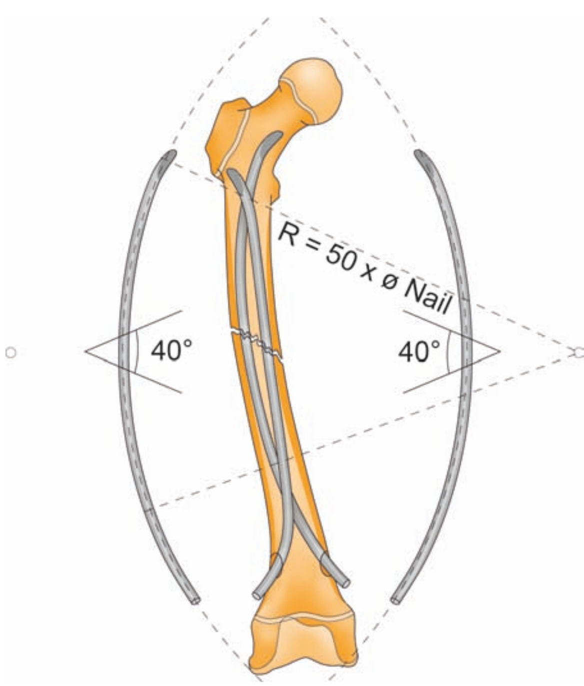

Fig. 5.6 Nail contouring. The two nails have opposing curves. The radius of curvature must be about 50–60 times greater than the diameter of the nail. The apex of the curve must be located at the fracture site, here, in the middle third of the bone

5.2.6 The Ideal Nail

The ideal nail is one which easily finds its way to the fracture site through the medullary canal. A rounded end with a perfect curve is ideal to allow smooth gliding of nail along the inner wall of the medullary canal. Radius of curvature of the nail tip (4 times the diameter of the nail) has been well thought out. As a result, the outer curve of the leading end promotes gliding of the nail along the inner cortex of the medullary canal.

Additionally, to facilitate penetration of the dense cancellous bone of the metaphysis (or even the epiphysis) in metaphyseal fractures, the nail features a tapered end that is obtained by gradual flattening of the concave side of the tip (Fig. 5.7a).

The length of the curved tip should of course be proportional to the diameter of the nail. The longer the curved tip, the easier its insertion into the bone. However, it should be kept in mind that excessive length is not desirable as the nail may get stuck in the bone. Considering that the diameter of the nail must be 40% of that of the medullary canal, its maximum projected length must not exceed 2.5 times the diameter of the nail (100% of the canal diameter). This is why a mean length 2.2 times greater than the nail diameter (85–90% of the canal diameter) actually addresses the anatomic spectrum (Fig. 5.7a).

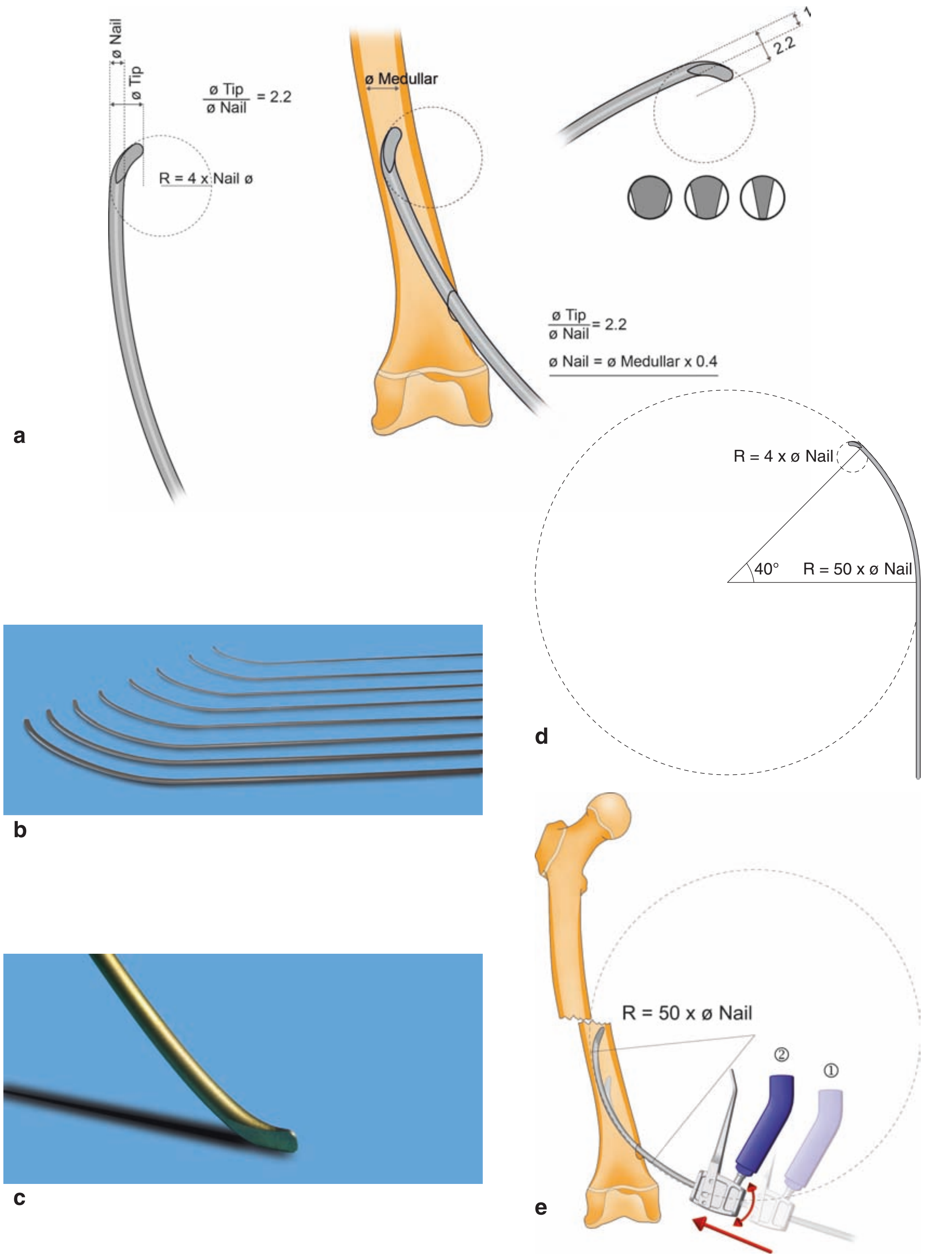

Fig. 5.7 The ideal nail. (**a**) Tip shows a perfect curve with a diameter 4 times that of the nail, an outer curve and a tapered end. The projected length of the curved tip is about 2.2 times greater than the diameter of the nail (85–90% of canal diameter); (**b**) nail diameter range from 1.5 to 4.0 mm; (**c**) tapered tip of the nail; (**d**) the optimized built-in curve at the leading end facilitates later contouring; (**e**) adequate bending makes it easy to advance the nail through the medullary canal

A nail design with an optimized built-in curve at the leading end greatly facilitates the surgeon's work in the operating room. It indicates the overall curvature that must be achieved to finally have the apex of the curve located at the fracture site in diaphyseal fractures. In metaphyseal fractures, no further contouring is necessary. The radius of curvature should be about 50–60 times greater than the diameter of the nail (Fig. 5.7b). A nail with an optimal curve of about 40° has the ideal shape to reach the fracture site without difficulty (Fig. 5.7c).

5.3 Dedicated Instruments

FIN should be performed with simple, though specially designed instruments, particularly if 3.5 or 4.0 mm diameter nails are used. As usual, the surgical

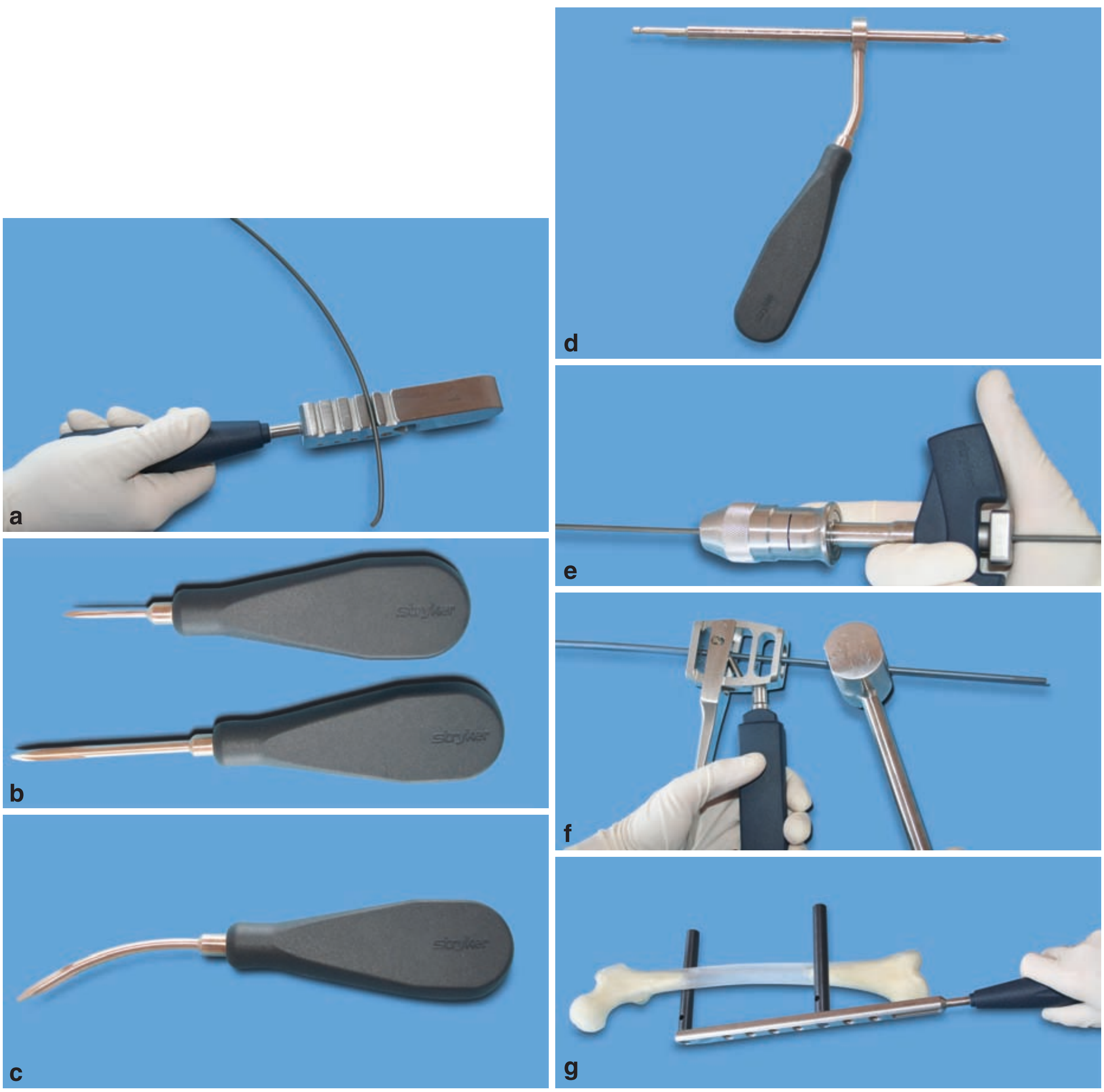

Fig. 5.8 Instruments. (**a**) Bending iron to bend (or unbend) the nail; (**b**) small and large awl to open the cortex; (**c**) curved awl to facilitate the nail passage through the bone; (**d**) tissue protective sleeve and drill; (**e**) T handle; (**f**) inserter and slotted hammer; (**g**) reduction F-tool to reduce the fracture

technique begins with a skin incision that is made over the planned entry point, and dissection is carried down to the bone surface.

The following instruments are required:

- X-ray ruler – a partly radiolucent calibrated ruler that is used to determine the appropriate nail diameter according to the width of the medullary canal.
- Bending iron – hand contouring is possible, but the use of a specially designed instrument is most helpful. It is imperative to create a smooth, uniform curvature with a radius about 50 times greater than the diameter of the nail. Sharp and severe bends should be avoided (Fig. 5.8a).
- Awl – it is used to create the entry hole into the cortical bone of the metaphysis. It should be

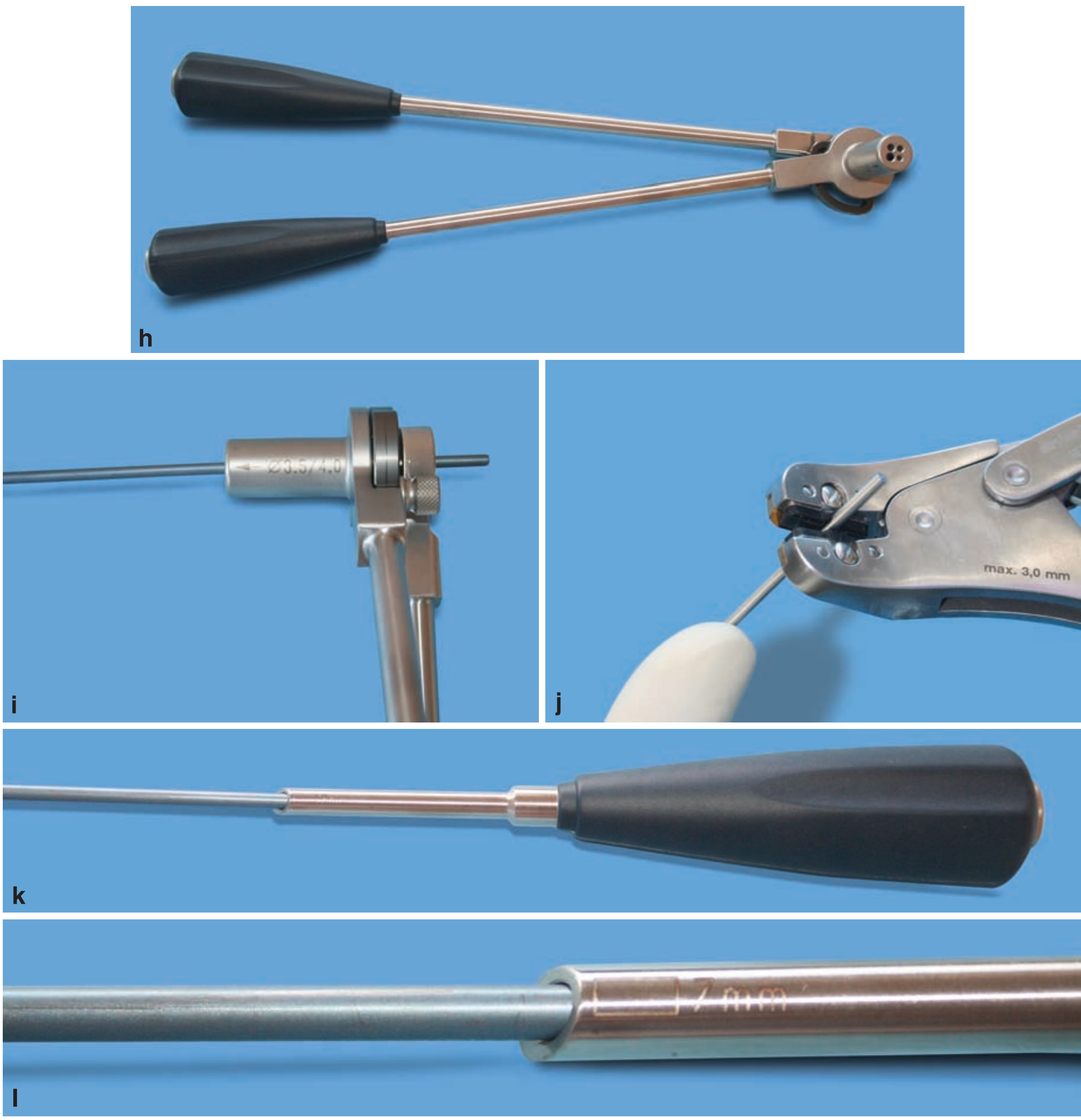

Fig. 5.8 (*cont.*) (**h**) atraumatic large nail cutter; (**i**) close up view of large cutter; (**j**) atraumatic small nail cutter; (**k**) cannulated impactor with nail inside; (**l**) close up view of cannulated impactor with depth mark

slightly larger than the diameter of the selected nails. Its ergonomically designed handle provides good tactile feedback and control, thus minimizing the potential for slippage. The tip of the awl should be short enough to allow placement of a finger to protect against injury in case of slippage (Figs. 5.8b, c).

- Drill bit – in hard cortical bone, it may be necessary to drill the entry hole using a drill bit with a diameter slightly larger than that of the selected nail.
- Tissue protection sleeve – it is intended to be used with the awl or the drill bit. Its sharp teeth grip the bone securely. It has the same length as the awl/drill bit, which eliminates the risk of penetration of the far cortex (Fig. 5.8d). T-handle – it provides firm hold of the nail, allowing the surgeon to apply oscillary rotary motions, advance the nail into the medullary canal, and complete reduction. It must be easy to tighten and loosen, and must not slide over the nail. The surgeon should position his/her hand so as to avoid injury in case of accidental slide of the T-handle, resulting in sudden backout of the nail (Fig. 5.8e). For large diameter nails, compared to all the handles currently available on the market, the inserter has proved the most efficient gripping tool. Furthermore, it accepts contoured nails. One last requirement for an appropriate handle: it should have a strong metal surface that withstands firm hammering (Fig. 5.8f);
- Reduction F-tool – it features a radiolucent carbon fiber handle and ajustable transverse rods that assist in reducing the fracture while protecting the surgeon's hands from exposure to the image intensifier. The concave shape of the transverse rods minimizes trauma to the tissue, provides even distribution of pressures on thigh muscles, and reduces the risk of muscle bruising (Fig. 5.8g).
- Slotted hammer – once the nail tip is properly oriented, the nail is pushed across the fracture site with the help of the slotted hammer. With hand pushing, rotation of the T-handle would most often misdirect the nail toward soft tissue. At the end of the procedure, impaction of the fracture site is also performed using the slotted hammer. The advantage of using a slotted hammer is that the hammer slides up and down the nail without the handle interfering with the nail. It is also used at the end of the procedure with the impactors.

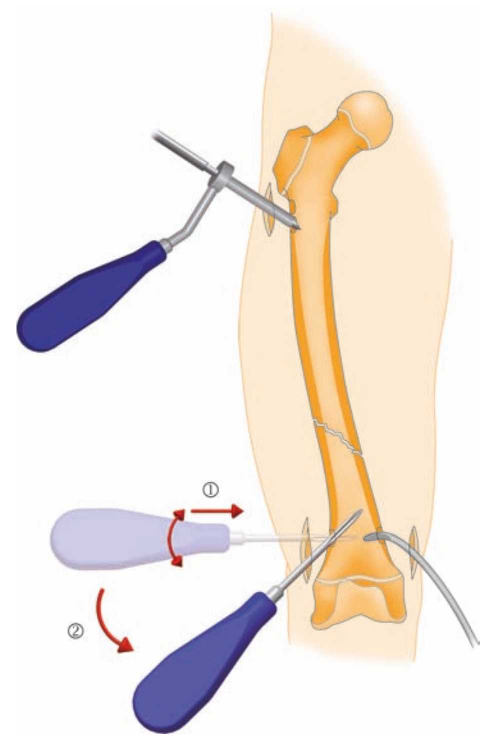

Fig. 5.9 Entry hole can be created with an awl or a drill bit. Diameter of the twist drill is 1–2 mm larger than that of the nail. Note the position of the entry hole relative to the skin incision, and the direction of the awl (toward the diaphysis)

- Nail cutter – the ideal instrument is a guillotine-style cutter that provides a smooth clean cut. The sectioned end is rather blunt and atraumatic (Fig. 5.8h–j).
- Cannulated impactor – it is intended to push the nail forward, and leave sufficient length proud of the bone surface to facilitate later removal while not causing skin irritation (Fig. 5.8k, l). This impactor must not be used to rotate the nail, but it can be used to bend the trailing end prior to trimming. This "smart" impactor features a variable length cannulation: due to the bevel of the tip, length varies according to the position of the impactor on the bone surface. By rotating the impactor, one can change the depth of the cannulation. Depth marks are provided on the impactor for reference. With large diameter nails, the portion that exits the bone ranges from 7 to 12 mm in length, and with small diameter nails, from 3 to 5 mm.

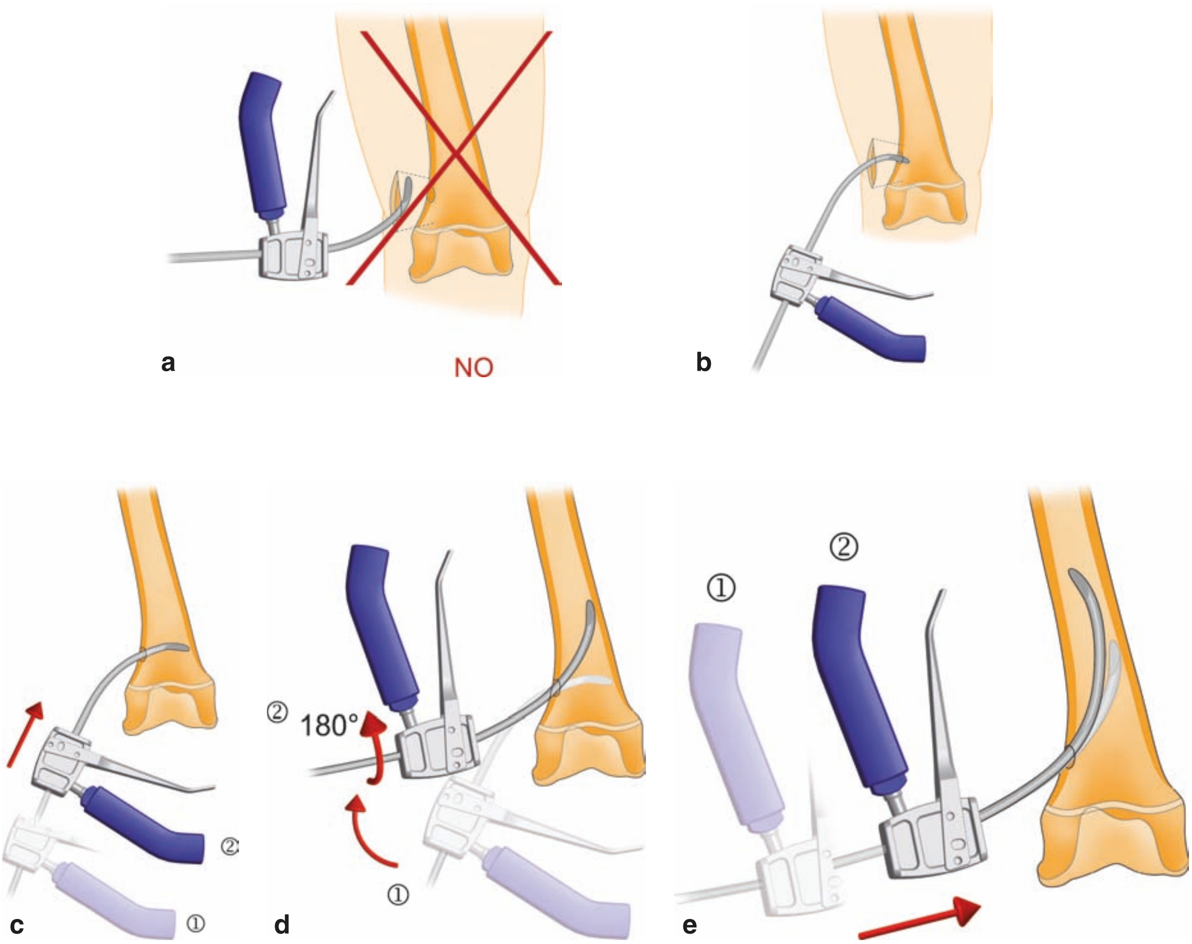

Fig. 5.10 Nail insertion. (**a**) Entry hole is located at the "diaphyseal end" of the skin incision. The nail must not be positioned parallel (**a**); **b**, **c** but perpendicular to the bone surface. (**d**) It is then rotated 180°, (**e**) and inserted into the medullary canal

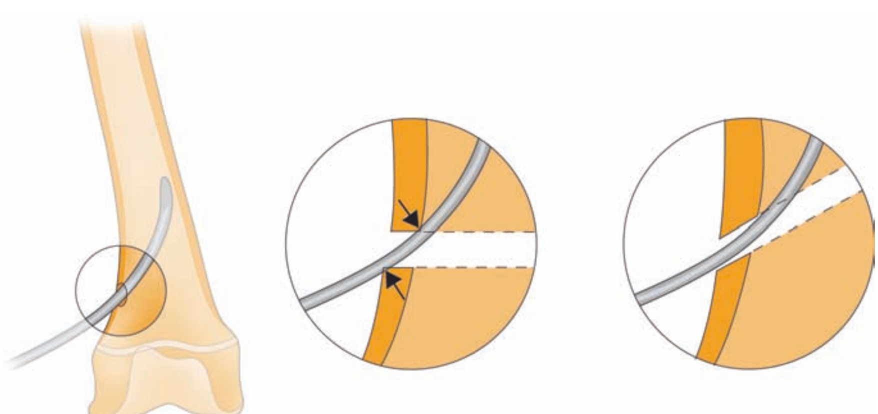

Fig. 5.11 Importance of the oblique direction of the entry hole. Due to friction forces, a nail that is inserted perpendicular to the hole cannot be advanced into the medullary canal

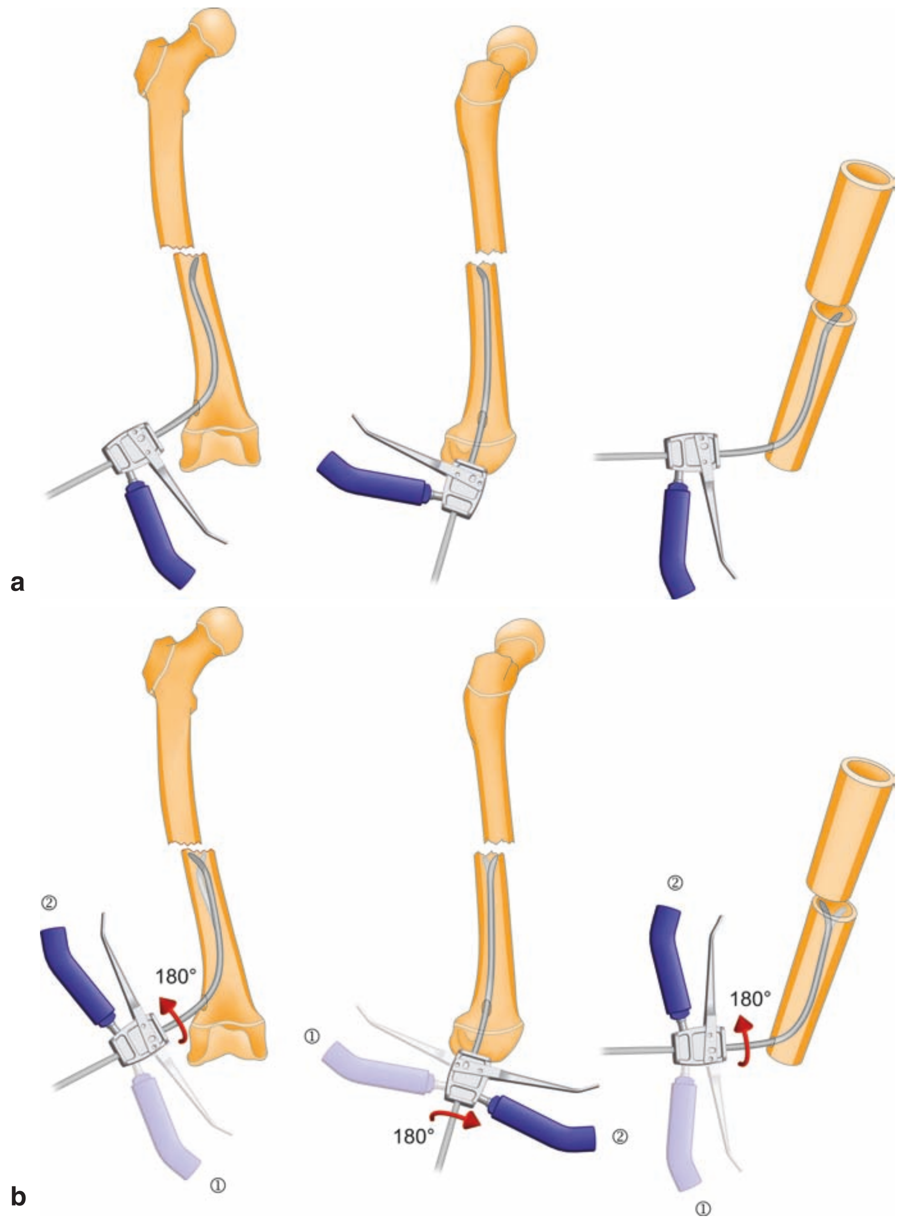

Fig. 5.12 Crossing of the fracture site. (**a**) Here, nail tip is initially directed medially, posterior to the opposite fragment. (**b**) Once rotated 180°, its tip points laterally and anteriorly, which permits passage

Some additional instruments are particularly helpful for removal of hardware:

- Curved osteotome – it may be necessary to remove any bone overgrowth (Fig. 7.1, Chap. 7).
- Locking forceps – they must have a good holding power. For removal of 3 and 4 mm nails, forceps with a lateral impaction stud (allowing the use of a slotted hammer) are more appropriate. Another particularly useful feature is a threaded end for attachment of a slotted hammer (Fig. 7.2, Chap. 7). Furthermore, these forceps may be used during nail insertion to adjust the curvature of the leading end in case it does not fit the anatomy.

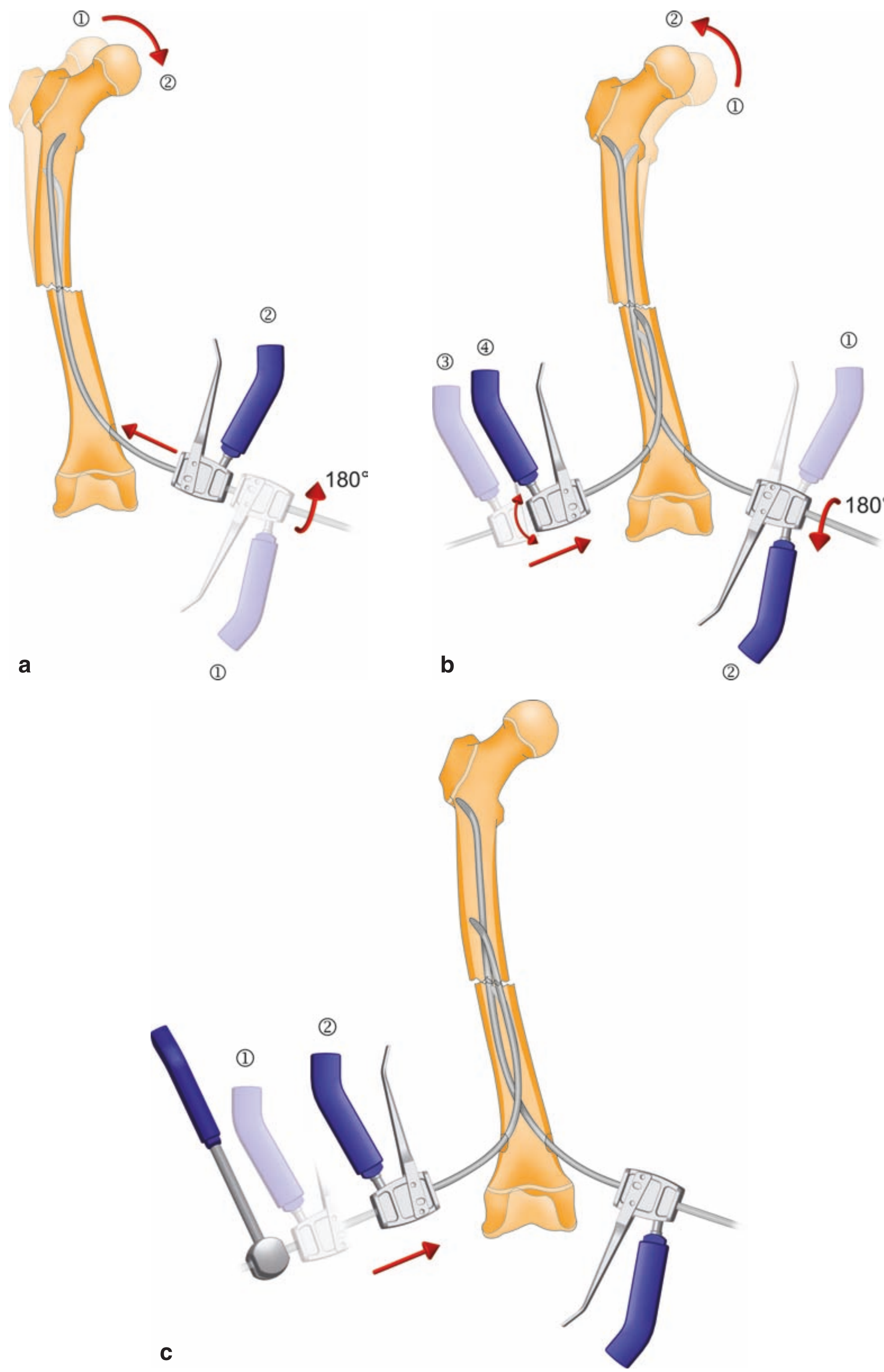

Fig. 5.13 (**a**) Advancing one nail up the proximal fragment may result in varus angulation due to nail contouring. (**b**) Rotation of the nail realigns bone fragments and allows passage of the second nail. (**c**) The second nail is pushed across the fracture site using a slotted hammer

5.4 Surgical Technique

Patient positioning depends on the location of the fracture. The affected limb is sterile prepped. An attempt at closed reduction with external maneuvers is initially performed using the image intensifier (AP and lateral. views) to check for reducibility. It is important to memorize the maneuvers that will be used intraoperatively.

Depending on the selected nailing technique, the skin incision is often made in the metaphyseal region, that is, close to the growth plate. If a percutaneous approach can be used, the surgeon should keep in mind that the incision will have to be extended for removal of hardware, which will be badly tolerated both by the child and the family. For this reason, it is advisable to make right away a 15–30 mm incision (for radius and femur respectively), which allows retraction of superficial veins and sensory nerves (as is the case in the radius), muscle dissection in line with their fibers, and, if necessary, incision of the periosteum, which is partially elevated. Then, two retractors are enough to allow good visualization of the bone.

Due to the oblique direction of the nail, the entry hole should be positioned at the "diaphyseal end" of the incision to minimize skin impingement at the "epiphyseal metaphyseal end" of the incision during insertion. This reduces the risk of "tattoos" caused by metal debris from the implant surface.

The entry hole into the cortical bone is usually made with an awl. The instrument is initially positioned perpendicular to the bone surface, and then directed toward the fracture site. During this step, it is recommended to place a finger on the tip of the awl to protect against soft tissue injury in case of slippage. The surgeon can easily feel the position of the tip in the bone. In particularly hard and dense bone, power drilling is recommended using a drill bit 1–2 mm larger than the diameter of the nail (Fig. 5.9). It is routinely used in lateral subtrochanteric approach to the femur or in the humeral shaft. The tissue protection sleeve that is firmly anchored in bone provides increased safety by avoiding the risk of inadvertent slippage of the awl or drill bit.

The nail is attached to the T-handle (or the inserter) and inserted into the bone through the entry hole, with its curved tip properly oriented. There are two reliable, easy-to-find landmarks: the entry hole is normally located straight below the incision end that is close to the fracture site, and at the apex of the convexity of the bone. Prior dissection should have been carried out longitudinally (only) in order to minimize distension of

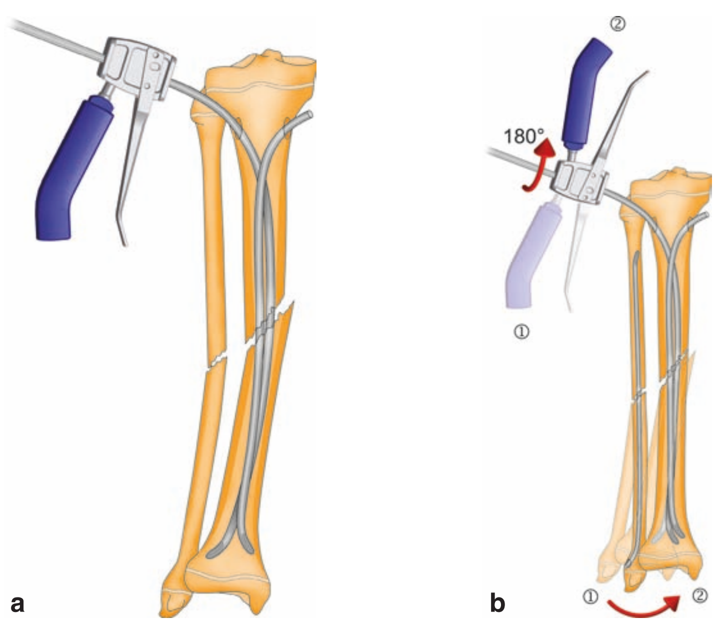

Fig. 5.14 (**a**) Valgus angulation in the tibia. (**b**) The lateral nail is rotated 180° to drive the distal fragment medially and thus correct the angulation. Retrograde insertion of a third fibular nail may be considered

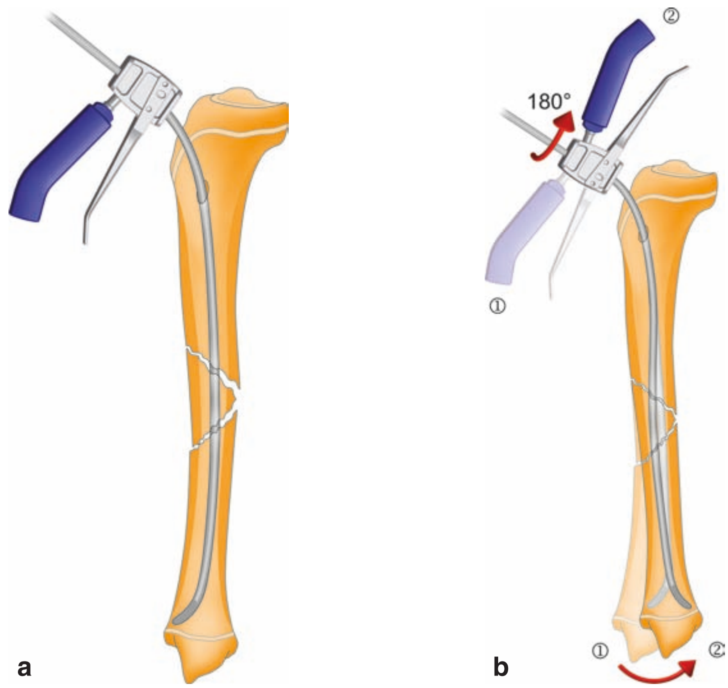

Fig. 5.15 Tibial fracture (**a**). AP view. (**b**) Recurvatum angulation is corrected by rotating one of the nails 180°

soft tissue spaces. Nail tip should be positioned perpendicular to the bone surface, and as soon as it has passed the cortex, it is directed toward the fracture line. Obviously, if the nail tip is advanced parallel to the cortex, it will never enter the medullary canal. Tactile feedback differs when the tip of the nail makes contact with the far cortex. Then, the nail smoothly glides along the inner wall of the medullary canal with the aid of slight rotary movements (clockwise and counterclockwise) of the inserter (Fig. 5.10). Access to the medullary canal is facilitated by the oblique direction of the entry path (Fig. 5.11). When the fracture site is reached, the tip must be oriented so that it sits right in front of the opposite fragment (AP and lateral). The fracture is reduced, and reduction is checked using fluoroscopy (AP and lateral) (Fig. 5.12). Then, the nail is pushed across the fracture site using a slotted hammer, and advanced by hand into the opposite fragment.

The second nail is attached to the T-handle (or the inserter), and inserted in the same manner. Crossing of the fracture site can be performed either immediately after the first nail or when the first nail is well engaged in the fragment. In the first case, the curved end of the nail assists in maintaining reduction, which facilitates passage of the second nail (Fig. 5.13). The second option offers greater stability but leaves less room for the second nail to pass. More space can be gained by rotating the first nail. Once the second nail is properly oriented, it is pushed across the fracture site, using the slotted hammer.

Then, both nails are advanced until they reach the metaphysis, where they may be rotated to achieve perfect reduction of the fracture. Nail contouring is most useful to control the corrective forces, and adjust them according to local stresses. Varus/valgus angulation can be addressed by directing the nail tips medially or laterally, as appropriate, to counter the angulation forces. A varus angulation can be corrected by directing the nail tip laterally, whereas a valgus angulation can be corrected by directing the nail tip medially (Fig. 5.14). Similarly, in the sagittal plane, a recurvatum angulation can be corrected by directing the nail tips posteriorly, and a flexion angulation by directing the nail tips so that the concave sides face anteriorly (Fig. 5.15). Combined deformities can also be addressed. For instance, a combined valgus-recurvatum angulation can be corrected by changing the direction of nail tips so that their convex sides face anterolaterally. Once the position and

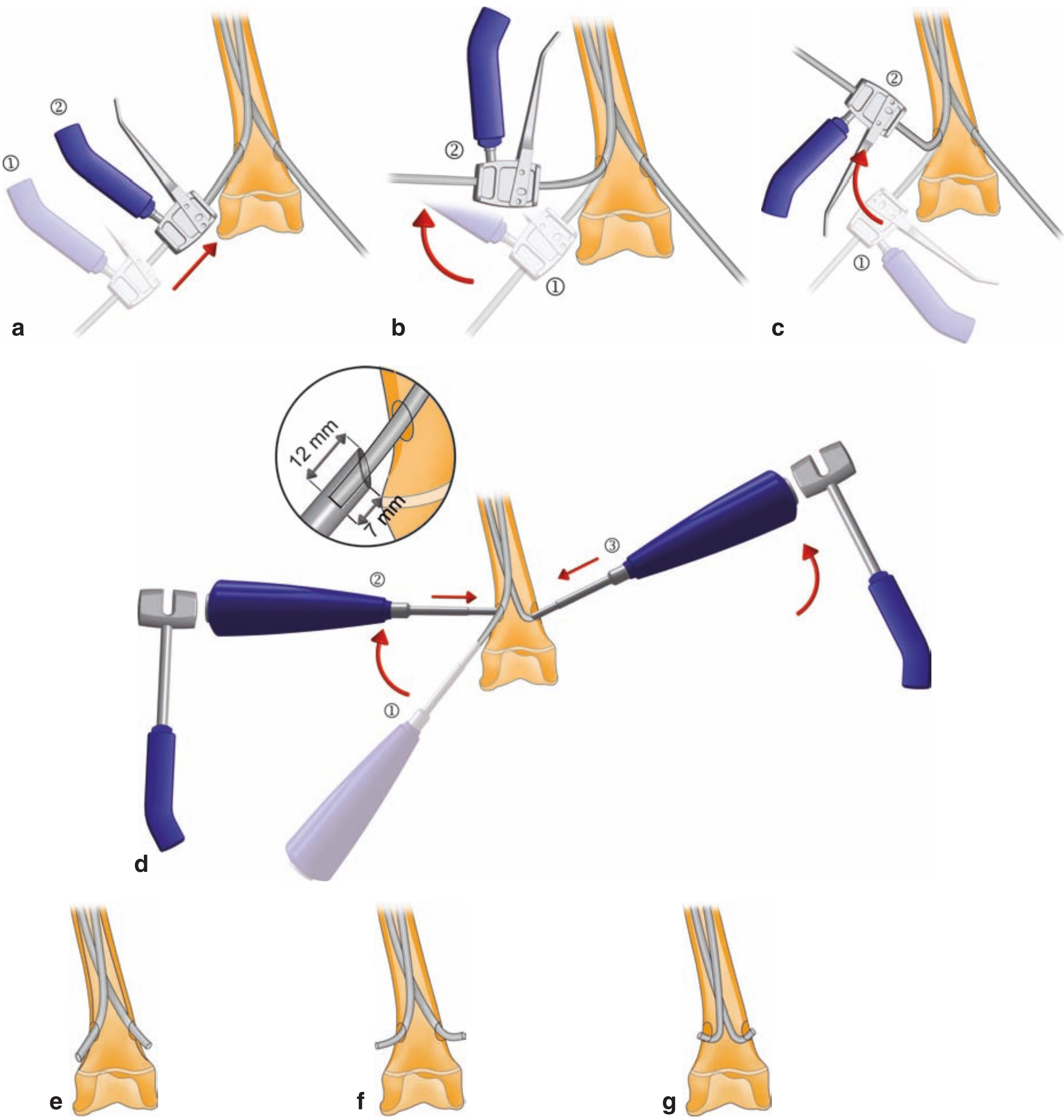

Fig. 5.16 Bending and impaction of the nails. (**a**) One option is to simply push the nails and let them lie against the distal cortex. (**b**) A second option is to bend the nails to about 30–60° flush to the metaphyseal cortex. (**c**) A third one is to overbend them and recess the bend into the bone; the aim is to get a strong anchorage distally to avoid any risk of migration. (**d**) Different ways to use the impactor. Position of the nails after trimming. (**e**) Nail end is recessed using the cannulated impactor; (**f**) after it has been bent to 45°. (**g**) The nail end may be sharply bent and fully recessed into the bone using an impactor

orientation of both nails are satisfactory, they are impacted into the cancellous bone of the metaphysis while maintaining reduction. Attention should be paid to the horizontal plane at all times during this reduction step so as to prevent rotational malunion. As a matter of fact, it is unlikely that rotational malunion will ever be fully corrected during the remaining growth period.

The last step, but not the least, is the final impaction of the fracture site. It plays an important role in final reduction. All transverse fractures must be impacted to

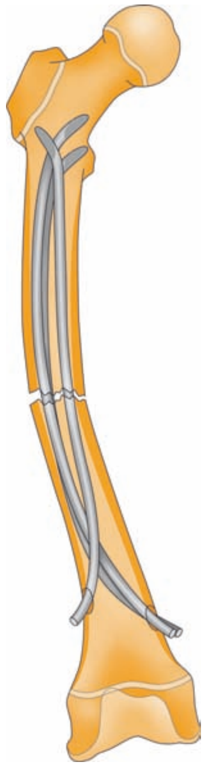

Fig. 5.17 Asymmetric malaligned construct: two nails opposed to one nail, entry holes are not symmetrically positioned, radii of curvature are different, nails do not have the same diameter

minimize the potential for later leg length discrepancy. In oblique and spiral fractures, and even fractures with a third fragment, impaction provides stabilization of the fracture site at the expense of slight shortening (5–10 mm), which is readily compensated for by postoperative overgrowth. Furthermore, impacted nails are trimmed to the proper length, which eliminates the risk of postoperative prominence due to spontaneous impaction of the fracture site.

Trailing ends are generally bent to about 45° prior to trimming. They can be recessed into the medullary canal using the appropriate impactor, while leaving sufficient length proud of the bone surface to facilitate later removal. In some cases, the trailing ends are not bent; they are simply allowed to lie against the cortical wall after trimming. The third option is to sharply bend the trailing ends (>90°) and fully recess them into the bone, where they will stay, more or less permanently (Fig. 5.16).

Routine closure is performed using a few subcutaneous sutures and intradermal running sutures (slow absorption monofilament sutures). AP and lateral X-rays

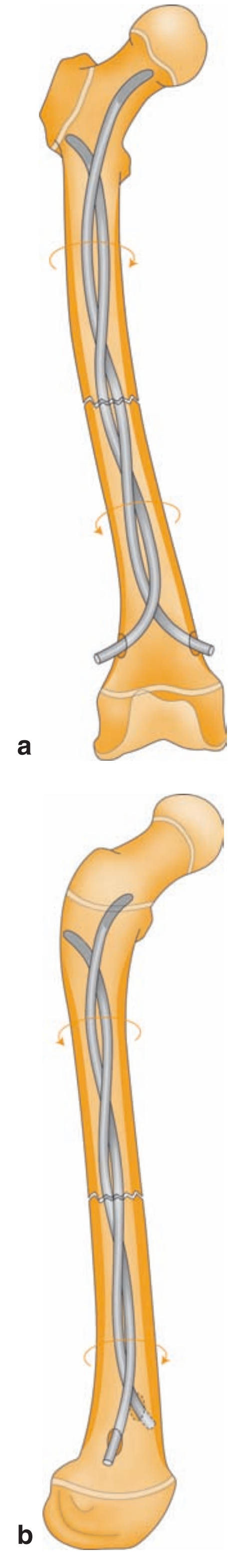

Fig. 5.18 Second nail is entangled with the first one, (**a**) which alters both the frontal (**b**) and sagittal axes

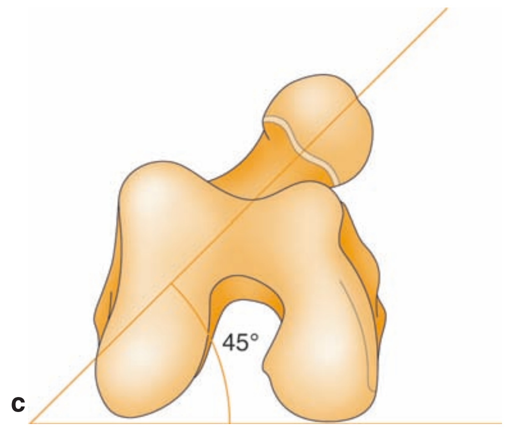

Fig. 5.18 (*cont.*) (**c**) and also the horizontal plane. Here, there is a 45° anteversion of the femoral neck

are taken for immediate checking, and a compressive dressing is applied for 48 h.

In short, there are altogether four reduction steps:

- Before surgery, to memorize the appropriate reduction maneuvers and check for reducibility of the fracture by closed means.
- Intraoperatively, to allow the nails to cross the fracture site.
- At the end of the procedure, to complete reduction by properly rotating and orienting the nails.
- Lastly, final impaction of the fracture site is performed prior to nail trimming.

5.5 Pitfalls

Stability of FIN depends on a number of factors, including appropriate nail diameter, symmetric construct, proper orientation of corrective forces (opposite to those causing displacement), and quality of the technique. The surgeon must be able to adapt to multiple surgical realities, analyze the situation, and determine the best solution:

- Undersized nails are prone to buckling, which results in unacceptable angulation of the fracture site. Therefore, the surgeon must respect the all-important rule of FIN: diameter of the nail > 40% of the diameter of the medullary canal.
- Asymmetric constructs should only be used if absolutely necessary (Fig. 5.17). Even-size nails should be inserted through entry holes, which are symmetrically located on the bone. They should be consistently bent and contoured so that their concavities face each other, and the nails do not intersect at the fracture site: both nails must cross each other proximal and distal to the fracture site.
- The nails must not get entangled: the second nail should be advanced with the aid of slight rotary movements (clockwise and counterclockwise). Should entanglement occur, the surgeon would not control reduction. It would be dictated by the awkward construct achieved (Fig. 5.18).

If inadequate reduction due to faulty technique is discovered intraoperatively, the best thing to do is to switch to open surgery, and revise FIN to achieve a perfect construct. It is self-evident in case of asymmetric construct or entanglement. However, in rare instances, the use of a third nail may help correct residual displacement. Its role will be to counter the angulation forces. Here, we are reaching the limitations of the technique, but several options are available: cast immobilization, gypsotomy (if necessary), conversion to another treatment method such as intramedullary nailing for the femur or the tibia – depending on the age of the child – or external fixator.

5.6 Complications

5.6.1 Prominent Nail Ends

Nail ends are normally palpable under the skin, as a few millimeters must be left proud of the bone surface for later removal. The few postoperative complications associated with prominent nail ends can, however, be minimized by:

- Impacting the fracture site prior to trimming nail ends.
- Trimming nail ends with a guillotine-style cutter, which provides a smooth clean cut (Fig. 5.8h).
- By placing a protective end cap over the prominent end or by using a screw-in plug.
- Or by using fixed-length nails with rounded or bullet tips, or even Ender-type nails with distal locking screws.

Nail migration is a totally different problem. It may occur in severely porotic bone (e.g., osteogenesis imperfecta, neuromuscular diseases) or in severely comminuted fractures, which are highly unstable. Whether the end is too prominent or has broken through the skin, trimming to the appropriate length is necessary.

In a few patients, impaction of bone fragments required application of an external fixator to perform gradual distraction, and restore normal bone length within a few weeks. The fixator was removed after 1–2 months.

5.6.2 Delayed Union and Nonunion

No delayed unions or nonunions have been reported in fractures of the humerus, both bones of the forearm, and femur. But every orthopedic team has experienced at least one such complication in certain tibial fractures such as those seen in adolescents: complex fracture resulting from direct impact that is unstable and impossible to reduce nonoperatively, with a viable proximal physis that contraindicates the use of an intramedullary locked nail.

5.6.3 Osteomyelitis

Immediate postoperative infection is a rare occurrence after closed FIN. Osteomyelitis developed in patients suffering from cerebral palsy, in whom prominent nail ends eventually broke through the skin, resulting in localized bone infection. Overall, 0.3% of the patients had osteomyelitis, which, in most cases, occurred secondarily, and resolved with appropriate antibiotic therapy. In some patients, infection was diagnosed several months after hardware had been removed.

5.6.4 Malunion

An inadequate construct exposes to the risk of angular deviation, which is not acceptable in adolescents who have a limited bone remodeling capacity. Malunion is rarely seen in both bones of the forearm for a simple reason: reduction in both the frontal and sagittal planes cannot be but perfect, since each bone is nailed. Provided that the surgeon takes care to mobilize the forearm in pronation and supination at the end of the procedure, potential rotational malunion is avoided.

Rotational malunion may be seen in the femur [6], where reduction has not been performed in the horizontal plane. In the frontal plane, a postoperative axial correction of 10° can be achieved very gradually (maximum gain of 2° per year) in children aged less than 10 years at the time of the injury.

In regards to tibial fractures, reduction is sometimes so difficult to achieve that two-thirds of our fractures managed with FIN required adjunctive immobilization in a cast boot, plus gypsotomy in some cases, to maintain correct alignment.

5.6.5 Refractures and Recurrent Fractures

A certain number of patients sustained simple falls after their operation without this compromising the integrity of the construct. But we also had children who sustained severe trauma and refractured their bone with the nails in situ, and, of course, the nails got buckled. Manipulative reduction was successful in a certain number of patients with femoral or forearm fractures. In other patients, revision was necessary to achieve adequate reduction and stabilization of the new fracture.

Before 1987, nails used in both-bone forearm fractures were routinely removed within 3–4 months of the initial fracture. Four refractures occurred within a delay of 6 months, and were treated again with FIN. Since that time, we have gotten into the habit of leaving the nails in both bones of the forearm for more than 6 months, and we have no longer had any refracture or recurrent fracture [7].

5.6.6 Leg Length Discrepancy

A preexisting leg length discrepancy will be either compensated or worsened on the operated side. As will be discussed in the next chapters, the average amount of bone overgrowth after FIN is comparable to that observed with nonoperative treatments (i.e., 10 mm maximum in femur).

5.7 Conclusion

Prima facie, FIN looks quite easy, but a number of surgeons had to revise some of their cases due to inadequate construct. Performing a FIN is more than just building a construct. It requires a perfect understanding of biomechanics and skillfulness. Actually, it is pretty much like fine craft: the surgeon contours the nails by hand, and must have some degree of creativity to adapt to the patient's anatomy and properly orient the nails.

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6 FIN Without Image Intensification

Pierre Lascombes

Flexible intramedullary nailing (FIN) is performed using closed reduction whenever possible. The Healing process mainly relies on formation of external callus and endosteal callus, which is clearly enhanced by the presence of the intramedullary nails (see Chap. 2).

Our experience shows that open fractures and/or fractures treated by open reduction following unsuccessful external maneuvers have delayed healing. Still, no nonunions have been reported (Fig. 6.1), and postoperative course is hardly affected, since the nails provide effective protection against refracture caused by low-energy trauma.

As early as 1977, in Nancy, both-bone forearm fractures were treated by open reduction and internal fixation using Flexible Intramedullary Nails.

During the development phase of FIN, many young surgeons have visited us from Africa, South America, and Asia. They were all very impressed. When they left, they were eager to use it and popularize it in their own countries. But the BIG question was “how can we manage without image intensification?”

We prompted them to start using FIN without the help of the image intensifier using a direct approach to the fracture site.

6.1 Surgical Techniques (Fig. 6.2)

The patient is positioned supine on the operating table, whatever the bone segment to be treated. FIN is performed under general anesthesia. Initial insertion is the same as for a closed reduction technique, with the nails advanced into the medullary canal as far as the fracture site. Then, a direct approach is used for anatomic reduction and engagement of the opposite fragment under visual control.

Depending on the anatomic location of the fracture, length of the skin incision may range (in adolescents of the same age) from 40 mm for a forearm fracture to 60 mm for a femoral fracture. The fracture site is exposed using a direct approach carried along the intermuscular septa between the anatomic compartments, at some distance from critical neurovascular structures.

- Femoral fractures are best managed from a lateral approach. The iliotibial band is incised longitudinally, and the vastus lateralis is retracted anteriorly to afford access to the femoral shaft.
- In forearm fractures, the radius is approached anterolaterally between the ventral compartment and the lateral compartment. In distal-third fractures, the incision is preferably located on the ventral aspect of the bone. In proximal-third fractures, due to the deep position of the radius, the bone must also be approached between the ventral compartment and the lateral compartment to avoid injury to the radial nerve. Ulna is much easier to approach: directly from its posteromedial aspect, between the flexor and the extensor carpi ulnaris.
- For the tibia, the surgeon is free to use the approach he is most familiar with: anterior, medial, or anterolateral approach.
- Caution must be exercised when approaching the humerus laterally, due to the presence of the radial nerve, which courses around the posterolateral border in the middle shaft of the humerus. Depending on the location of the fracture site, a medial approach may be safer.

With a direct approach to the fracture site, the hematoma is evacuated during local debridement. Bone fragments are identified, and the medullary canal is located. Periosteal stripping is not desirable since periosteum has already been severely distorted during the injury.

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DOI: 10.1007/978-3-642-03031-4_6, © Springer-Verlag Berlin Heidelberg 2010

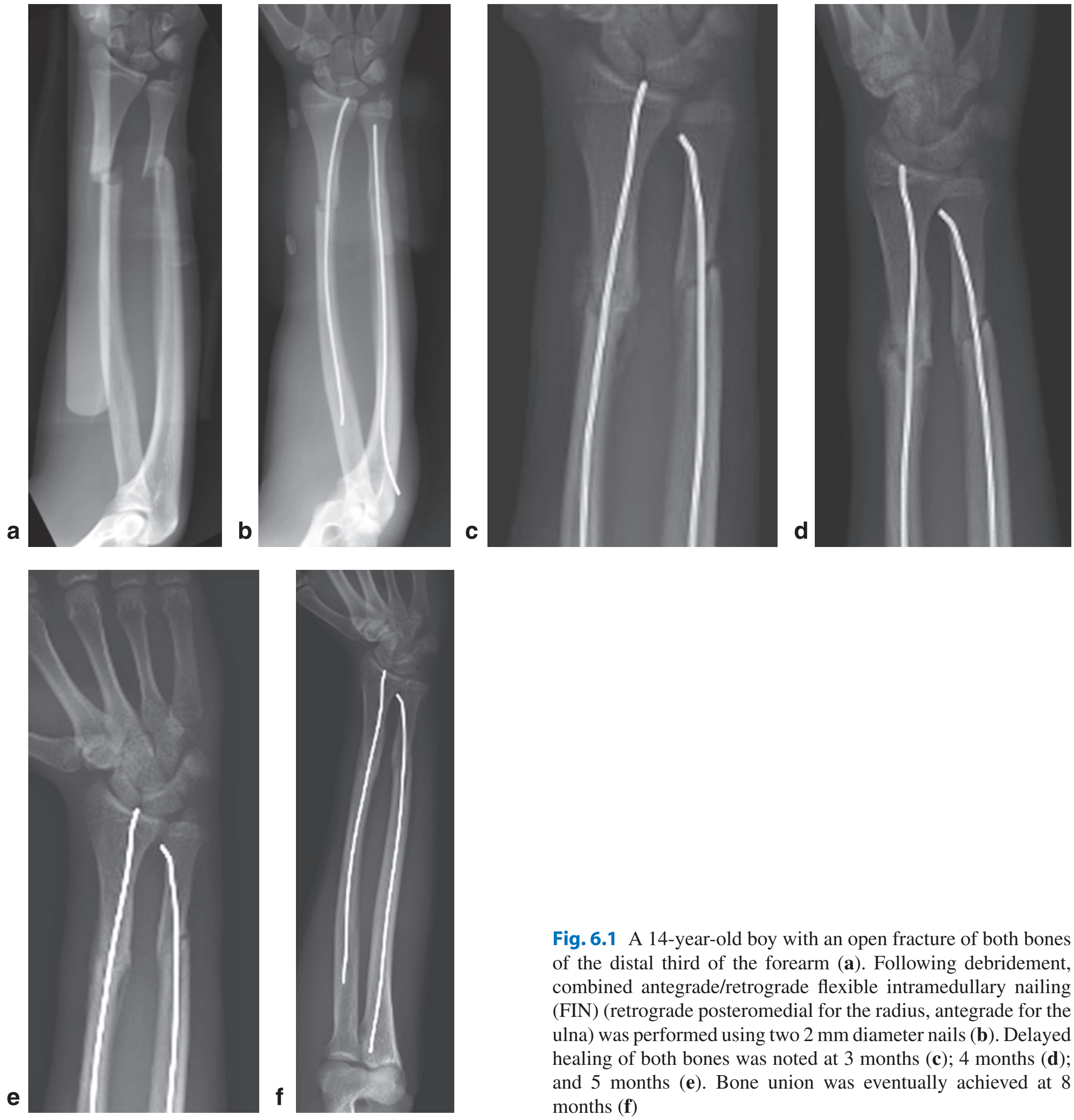

Fig. 6.1 A 14-year-old boy with an open fracture of both bones of the distal third of the forearm (**a**). Following debridement, combined antegrade/retrograde flexible intramedullary nailing (FIN) (retrograde posteromedial for the radius, antegrade for the ulna) was performed using two 2 mm diameter nails (**b**). Delayed healing of both bones was noted at 3 months (**c**); 4 months (**d**); and 5 months (**e**). Bone union was eventually achieved at 8 months (**f**)

One nail or two nails are advanced until they appear at the fracture site. Then, the leading ends of the nails are properly oriented so that they easily engage the opposite fragment. Some nails have a marker line, which greatly facilitates orientation of the nail tip. At this stage, the length X of the opposite fragment is measured from the metaphysis opposite the entry site to the fracture site, using reliable anatomic landmarks for reference. This measurement is transferred to the free end of the nail, and a mark is made for later reference.

Reduction is then performed using two reduction clamps. The nails can serve as tools to move the bone

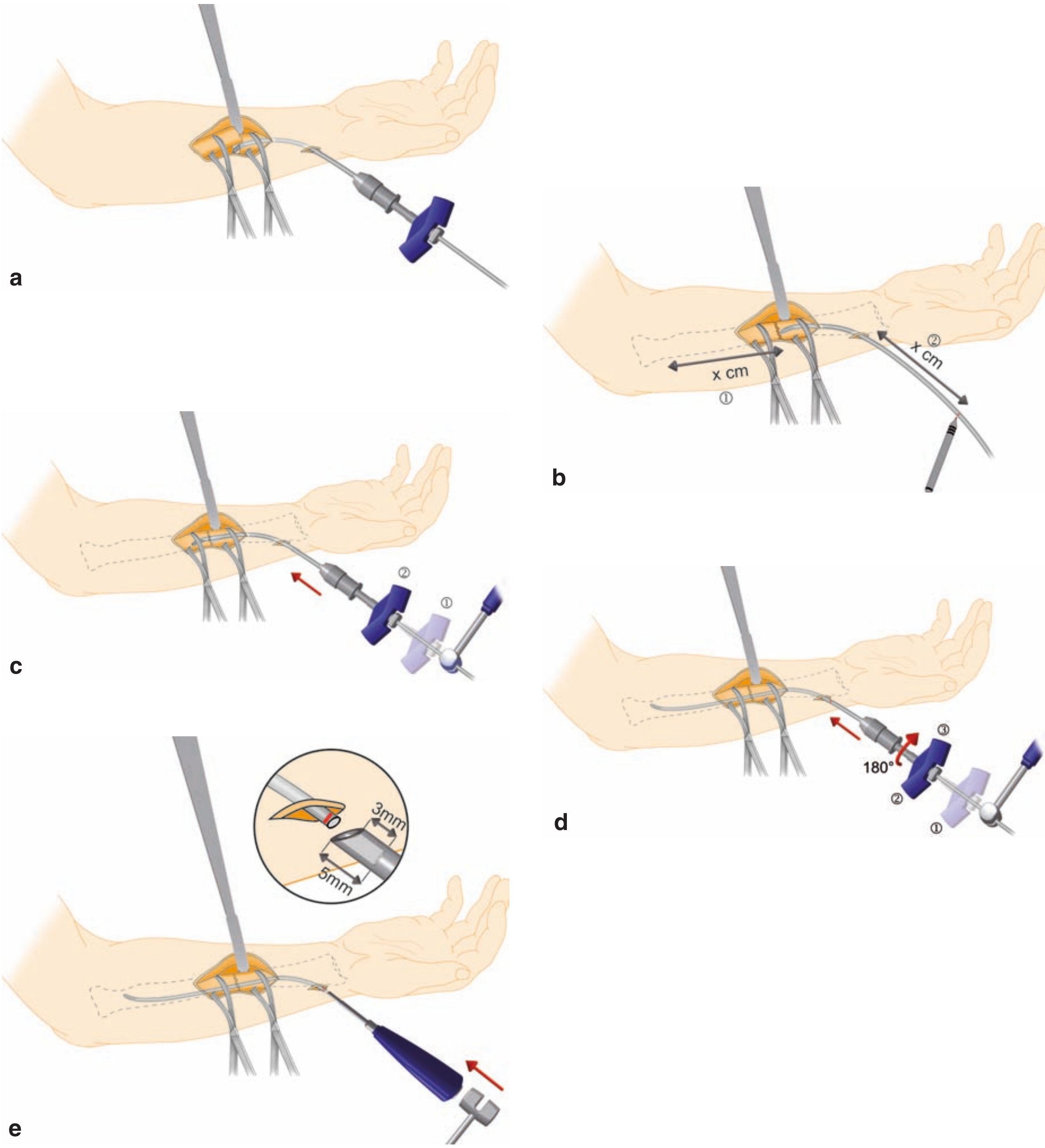

Fig. 6.2 Open FIN. Example of a radial fracture treated by retrograde FIN: one nail is inserted and advanced as far as the fracture site, and fracture site is opened (**a**). Reduction is performed using two reduction clamps. The length "X" of the proximal segment is measured *(1)* and measurement is transferred to the free end of the nail *(2)* (**b**). After the nail tip has been properly oriented, the nail is pushed across the fracture site with the help of a slotted hammer (**c**). The nail is advanced up the proximal fragment to the previously determined insertion depth "X" (**d**). If necessary, the nail is rotated to achieve optimal alignment of the fracture. The free end is then trimmed and recessed using the impactor (**e**)

fragment in which they lie. Then, the nails are pushed across the fracture site with the help of the slotted hammer, and advanced further until they reach the metaphysis. The mark previously made on the nail indicates proper insertion depth. Next, using the T-handle or the dedicated inserter, each nail is rotated so that it points to the right direction (with its concave side properly oriented), that is, the direction that allows alignment of the fracture. The reduction clamps are removed to check the quality and stability of reduction. Any residual angulation can be corrected by rotating the nails until stable, anatomic reduction is achieved. The free ends of the nails may be bent before trimming. Final impaction is performed as described in Chap. 5. Again, stability of the fracture site is assessed, and wounds are closed. It is up to the surgeon to decide whether drainage of the main wound (i.e., fracture site) is necessary.

In certain situations, the surgeon may select to leave the implants in situ. But this needs to be planned, as in this case, the trailing ends are simply recessed into the bone and buried to avoid irritation of the subcutaneous and cutaneous tissue.

6.2 Postoperative Care

Postoperative management does not differ from that described in each Chapter of this book, for each fracture location. Delayed healing that may be noted at the 3-month radiographic follow-up is only due to periosteal disruption and evacuation of the fracture hematoma. Subsequent radiographic assessments will confirm good healing of the fracture. At the most, the nails will be removed a few months later than recommended for closed FIN.

6.3 Conclusion

FIN can be safely performed without using intraoperative fluoroscopy. Furthermore, the free ends of the nails may be recessed and buried in bone for permanent implantation, if necessary.

Hardware Removal

7

Pierre Lascombes

Removal of a flexible intramedullary nailing (FIN) construct is often considered as a minor procedure. However, it is a specific procedure with specific requirements, which need to be emphasized. The first question is: is it legitimate to remove intramedullary nails in trauma cases? Several surgical teams around the world leave the nails in situ, while being aware of the long-term potential risks associated with permanent implantation: implant-related complications, difficulty to obtain good quality images, difficulty to perform other orthopedic procedures later on (e.g., additional internal fixation procedure, arthroplasty).

Some pathologies require that the nails be left for a long period or even permanently for protection of a weakened bone (i.e., neuromuscular diseases, cerebral palsy, osteogenesis imperfecta, bone cysts). These indications will be discussed later on in this book, but let's note here that in most cases, the free ends of the nails are initially cut as short as possible, and carefully recessed into the bone using a solid impactor.

The nails are generally removed, and both the child and the family must be informed of this before surgery.

7.1 Date of Removal

Metaphyseal fractures are generally united by 6–8 weeks, and nails are removed around the third postoperative month. In diaphyseal fractures of the humerus and tibia, the nails are removed about 3–4 months after surgery.

In the femur, the nails may be left up to 4–5 months, rarely longer as they would be too difficult to remove, particularly, the large-diameter titanium nails. In forearm fractures, the minimum implantation period is 6 months to allow for solid union of the cortices, and minimize the risk of recurrence of these fractures.

7.2 Surgical Protocol

The procedure is performed under general anesthesia. The affected limb is sterile prepped. The use of a tourniquet is recommended for the radius to avoid any risk of injury to the sensory branch of the radial nerve on the lateral aspect of the forearm. The skin incision should be long enough to allow for placement of the locking forceps after the nail end has been freed. If the periosteal bone has formed around the nail, it can be easily removed with a curved bone chisel (Fig. 7.1).

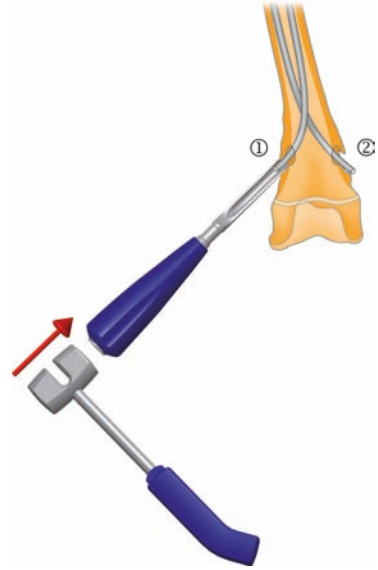

Fig. 7.1 Use of a curved bone chisel to remove bone overgrowth at the nail end

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DOI: 10.1007/978-3-642-03031-4_7, © Springer-Verlag Berlin Heidelberg 2010

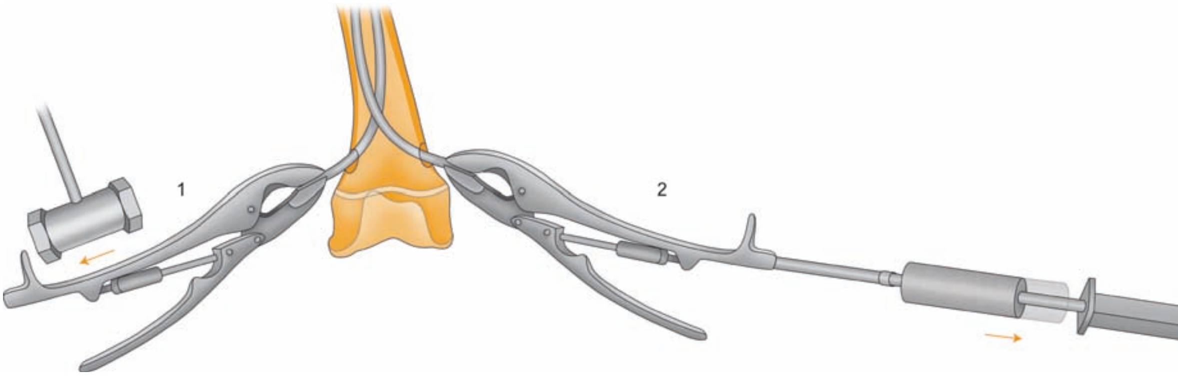

Fig. 7.2 Powerful locking forceps with an impaction stud for use with a mallet or a slotted hammer

Depending on the diameter of the nail, a length of about 5–10 mm should be left free to allow a firm grip. Selection of appropriate locking forceps is important: Facom™-type pliers with a longitudinal groove in one of the jaws for secure grip are a very good choice. Forceps with an extraction stud allow the use of a hammer. Forceps with a threaded end, allowing attachment of a slotted hammer, can be most helpful (Fig. 7.2).

7.3 Postoperative Care

Although immediate weight bearing is usually allowed, special precautions may be required in certain anatomic locations, where fractures at nail entry sites have been reported. The most vulnerable areas are those where the bone is very hard, as in the subtrochanteric region of the femur. Asking the child to refrain from sports for a few additional weeks is a reasonable safety measure.

7.4 Complications

Besides infectious complications, which may occur even in this uncomplicated procedure (or considered so), there is always a risk of splitting the bone during a difficult extraction (Fig. 7.3).

Another complication, which must not be overlooked, is the impossibility to remove the nails, generally when titanium nails have been left in situ for several years. In this case, it is better to leave them in place rather than attempt a potentially destructive procedure (Fig. 7.4) [1].

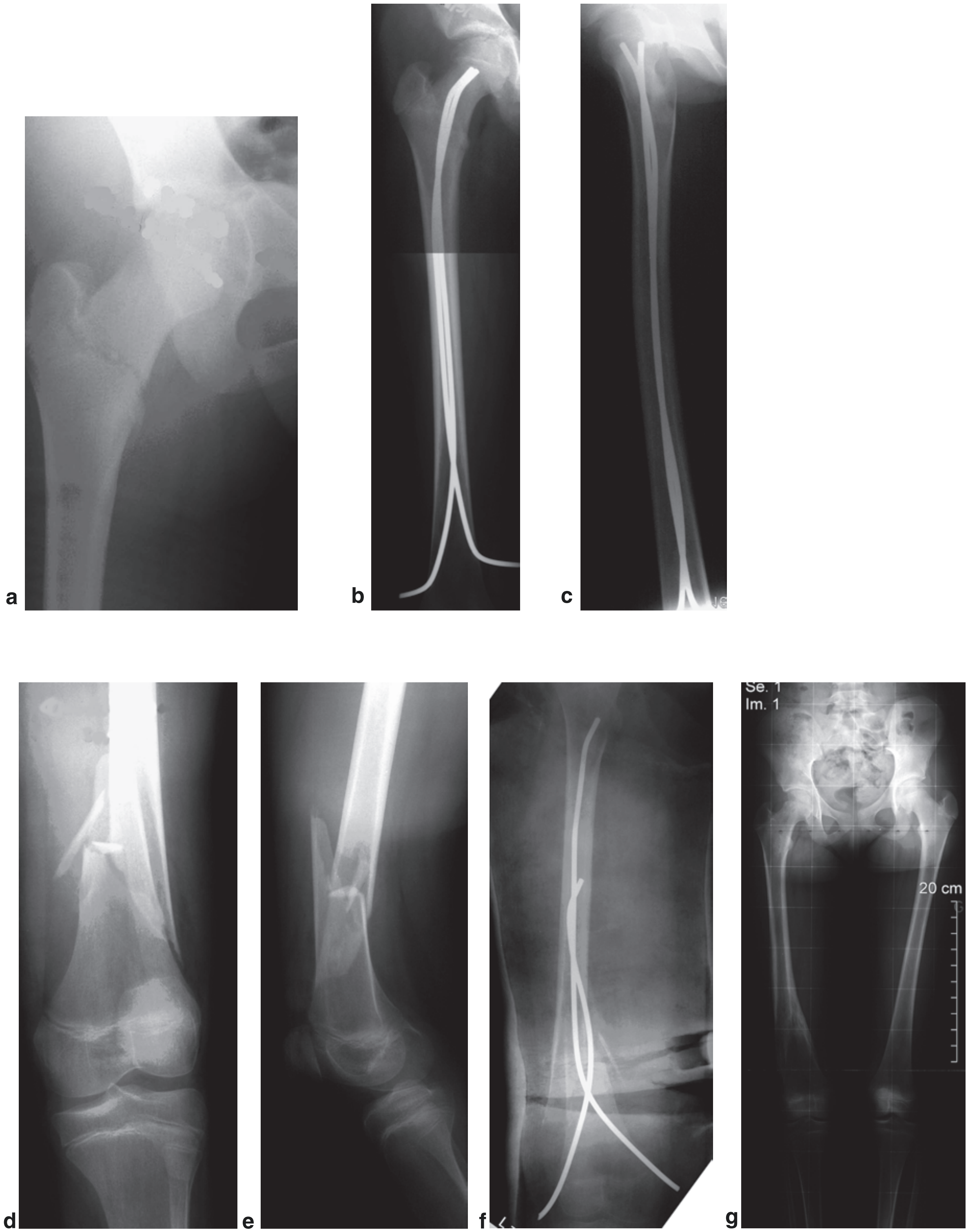

Fig. 7.3 1983: a 12-year-old girl with a basal neck fracture of the *right femur* sustained during a horse riding accident (**a**). Treated by flexible intramedullary nailing (FIN) (**b**, **c**). Nail removal performed 4 months later was arduous and resulted in distal fracture of the femoral shaft (**d**, **e**). Revision was performed a few days later using retrograde FIN plus cast immobilization and gypsotomy to correct postoperative varus angulation (**f**). At 2-year follow-up, axial alignment was restored with 10 mm shortening (**g**)

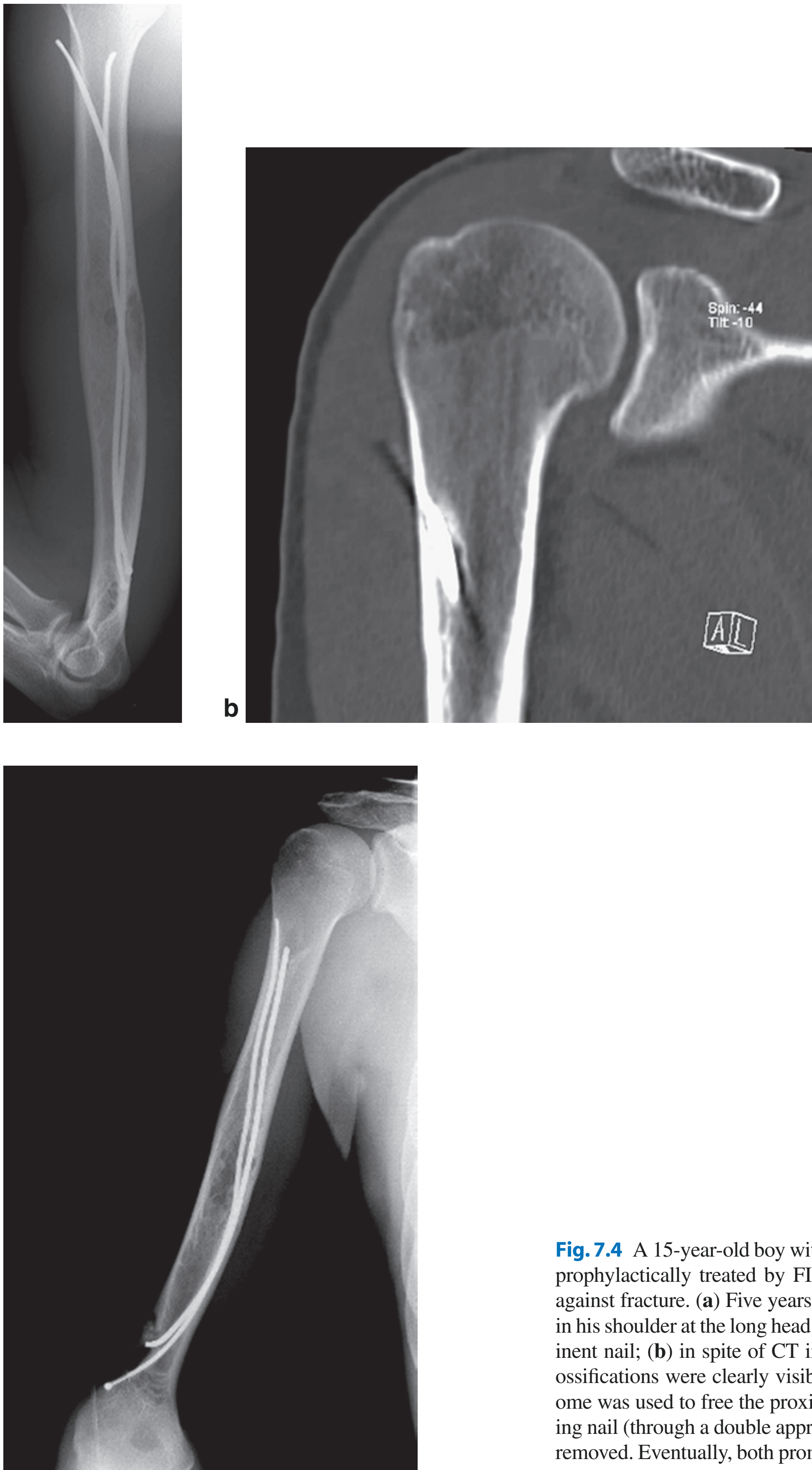

Fig. 7.4 A 15-year-old boy with diaphyseal aneurysmal bone cyst prophylactically treated by FIN of the *right humerus* to protect against fracture. (**a**) Five years later, the child complained of pain in his shoulder at the long head of the biceps tendon due to a prominent nail; (**b**) in spite of CT image artifacts due to the implants, ossifications were clearly visible along the nail; (**c**) a box osteotome was used to free the proximal and distal ends of the conflicting nail (through a double approach) but still, the nail could not be removed. Eventually, both prominent ends had to be cut flush with the bone surface to eliminate the cause of impingement

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8 Pediatric Anesthesia and Postoperative Pain Management

Anne Terrier

8.1 Anesthesia

Selection of the appropriate anesthetic technique for a child undergoing flexible intramedullary nailing (FIN) is based on several important factors, including emergency or elective surgery, anatomic location of the fracture, age of the child, patient's condition, and technical requirements.

In a Trauma Department, emergency cases are frequent. The child's anxiety may be increased when the parents are absent, and benzodiazepine premedication may attenuate the stress response. Analgesics should be given on admission: intravenous acetaminophen, associated or not with nalbuphine, provides pain relief without interfering with the anesthetics. Supplemental regional anesthesia may be used after ruling out any neurovascular lesions, particularly in femoral fractures (i.e., femoral nerve block or iliofascial block with or without neurostimulator, using a single injection of ropivacaine). In the upper extremity, the infraclavicular block is the preferred technique as it provides rapid pain relief, and contrary to the axillary block, it does not require mobilization of the limb. In children, search for multiple responses is not necessary, and single stimulation is sufficient. Potential risk of compartment syndrome in forearm and tibial fractures is a relative contraindication to regional anesthesia. Generally speaking, children admitted in emergency often have a full stomach, and surgery is delayed when possible, and if agreed by the operating surgeon. If not possible, rapid sequence drug-assisted intubation ("crush induction") under Sellick maneuver is performed if the child has no specific disease.

Prophylactic antibiotics (i.e., amoxicillin/clavulanic acid combination) are given to children with open fractures [2]. Furthermore, it is important to evaluate blood loss (if any) and estimate intraoperative blood loss, based on the clinical picture and biological tests.

In nontraumatic cases, many regional anesthetic techniques can be associated with general anesthesia, either pre or intra, or postoperatively. They have been shown to significantly reduce the use of analgesics, and provide substantial comfort intraoperatively, and above all, postoperatively. In the upper extremity, the supraclavicular block performed from a parascalene approach affords access to the interscalene space without endangering critical structures. It provides anesthesia for the entire brachial plexus area, plus, in 50% of the cases, the inferior part of the cervical plexus area. The axillary block is performed with the standard technique used in adults, with very low morbidity. Distal blocks can also be of interest in wrist or hand surgery (i.e., median and radial nerve block at the elbow, and ulnar nerve block at the wrist).

The infraclavicular approach allows placement of an in-dwelling catheter for efficient postoperative pain management.

In the lower extremity, caudal anesthesia or epidural anesthesia in older patients covers all lower limb territories. Both also allow placement of an in-dwelling catheter. Femoral nerve block and iliofascial block are easy to perform with or without catheter, and the proximal sciatic nerve block is performed from a lateral approach in the supine position.

In the foot, popliteal sciatic nerve block is often used through a posterior or lateral approach, with or without catheter.

Most of these techniques can be used in conscious, compliant children. However, most patients do not want to be awake, and so the blockade is often performed under general anesthesia. One must not forget that when a blockade is performed in a location where puncture is potentially dangerous, panic can be extremely detrimental.

Single stimulation is the rule in the young child. Determination of the local anesthetic dose is based on

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DOI: 10.1007/978-3-642-03031-4_8, © Springer-Verlag Berlin Heidelberg 2010

the age of the child (i.e., incomplete myelinization under 3 years of age, closely spaced nodes of Ranvier and small-diameter fibers in very young children, increased bioavailability and systemic absorption in infants) and on his/her weight. But the agents used are the same as those used in adults.

Anesthetic techniques are also age-dependent: mask induction is preferably used in young children; EMLA® patch facilitates intravenous cannulation in older children; regional anesthesia reduces the use of morphine, intra- and postoperatively; in very young children, caudal anesthesia is extensively used with or without adjuvant for all lower limb procedures; epidural anesthesia is reserved for older children. Monitoring is standard whatever the age of the child, and consists of: electrocardioscopy, pulse oximetry, noninvasive blood pressure monitoring, capnography, and of course, esophageal temperature monitoring. All patients are at risk of hypothermia, not only due to positioning, but also due to low temperature in the operating theater. Therefore, it is highly recommended to use a Bair Hugger®-type air-pulsed warming blanket. However, the increase in central body temperature, which may result from the use of a tourniquet, particularly in a bilateral procedure, should not be mistaken for malignant hyperthermia.

Lastly, with FIN, patient's condition plays an important role in pediatric anesthesia management.

8.1.1 Neuromuscular Diseases

Preanesthesia consultation with the anesthesiologist is of primary importance as cardiac, respiratory, and neurological functions are evaluated. Furthermore, it is important to check that there is no intubation problem in these children with potential stiffness, retraction, or deformities, to check for the presence/absence of macroglossia, and to assess the nutritional status and venous access. The use of succinylcholine and halogen agents is contraindicated. Some patients need postoperative respiratory assistance.

8.1.2 Osteogenesis Imperfecta

The psychological management of children with osteogenesis imperfecta, who often undergo multiple procedures, is of paramount importance. The use of succinylcholine is a relative contraindication due to the potential risk of fracture during muscle fasciculations; the use of a tourniquet is also proscribed in the severe forms. Brittleness of teeth in these children is another potential source of complications during intubation. The laryngeal mask airway may be a good alternative in some cases, and provides acceptable control of the airway.

8.1.3 As a General Rule

- Pressure areas must be carefully monitored.
- Antibiotic prophylaxis is instituted (second-generation cephalosporin as the first choice).
- Anticoagulants are given to high-risk patients (i.e., pubescent adolescents, obese adolescents, adolescents taking oral contraceptive pills) [1].
- Blood transfusion is used only if the hemoglobin level is lower than 6 g/dL.

8.2 Postoperative Pain Management

The goal of postoperative pain management is to achieve a visual analog scale (VAS) score less than three.

There are a few nonpharmacological methods and a variety of medications.

Parents have an important role to play. The benefits of their reassuring presence and physical contact with very young children have long been proven. It is also recommended that parents distract the child during care-giving and perform massages.

The currently available pharmaceutical armamentarium allows effective pain relief in children treated by FIN. Ketamine given intraoperatively blocks NMDA (N-Methyl-D-Aspartate) receptors, thus preventing hyperalgesia in some patients.

Pain medication is initially given before the child wakes up from anesthesia: acetaminophen (WHO level I analgesics) often combined in orthopedic surgery with a same level NSAID (non steroidal anti- inflammatory drug).

A pre or postoperative regional anesthesia generally allows differing the use of adjunctive level II analgesics, more especially, if a catheter has been placed.

Otherwise, nalbuphine (level II analgesics) is commonly used on a continuous or intermittent basis.

The use of level III analgesics is not uncommon in multiply operated patients. I.V. patient-controlled analgesia (PCA) with morphine can be used in older patients. Orally administered morphine can be used at an early stage.

In difficult cases, continuous infusion of sufentanil requires that the patient be treated in a resuscitation or intensive care unit for close monitoring. The main difficulty in postoperative pain management lies in the correct evaluation of pain intensity in a young child, even with all the scales available (objective pain scale [OPS], children's hospital of ontario eastern pain scale [CHEOPS]).

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9 FIN and Imaging

Laurence Mainard-Simard, Alain Noel, Luc Guillaume, and Michel Claudon

Flexible intramedullary nailing (FIN) is proven with over 25 years of clinical success, worldwide in the treatment of diaphyseal and metaphyseal fractures. Fluoroscopy is required for at least three surgical steps. The image intensifier is used during initial reduction of the fracture (AP and lateral), then during crossing of the fracture site, and lastly, to check the correct position of the nails and the quality of reduction. During the first two steps (i.e., initial reduction and crossing of the fracture site), the surgeon must maintain the reduction at all times, which means that he/she stands close to the radiation field.

In the beginning, those who objected to this method emphasized the risk of radiation for the child, and above all, for the surgeon. When used untimely and in inappropriate conditions, image intensification is, indeed, a nonnegligible source of radiation exposure. But for surgeons who are familiar with the use of image intensifiers, the benefits greatly outweigh the risks.

We shall first review basic information about ionizing radiation and its effect on the human body [1]. Then, we shall describe the good clinical practices and the measures that must be taken to protect both the child and the surgeon against radiation [2]. Lastly, we shall present the preliminary results of a prospective study conducted in the Nancy University Hospital Department of Pediatric Orthopedics headed by Prof. Lascombes. The goal of this work was to objectively record the radiation doses to the patient and the surgeon during an FIN procedure.

9.1 Ionizing Radiation and its Effect on the Human Body

Ionizing radiation has early, immediate effects or the so-called "deterministic effects." Ionizing radiation exhibits a threshold effect, which has been studied for each living tissue.

Early, immediate effects are seen with high-dose radiation. Radiation exposure can be voluntary as in radiotherapy or accidental. The severity of these effects depends on absorbed dose, and the onset time to effects depends on cell renewal. Radiation dermatitis, alopecia, cataract, bone marrow aplasia or fetal deformity are typical examples of deterministic effects.

The absorbed dose (Grays: Gy) is used to characterize immediate effects. It corresponds to the amount of energy imparted by ionizing particles to a unit mass of irradiated material.

As regards imaging, the focus was placed on the potential effects of low-dose ionizing radiation, which have long-term adverse effects on living cells (i.e., cancer and leukemia). These random effects are called "stochastic effects." They result from radiation-induced changes in cells (faulty repair of single-strand DNA breaks), and depend on the degree of harmfulness of ionizing radiation to the tissue. They are independent of absorbed dose. They are always serious, and the chances of seeing the effect (i.e., cancer or leukemia) increase with effective dose (ED).

For a given absorbed dose, generally expressed in milligrays (mGy), the long-term biological effects will depend on:

P. Lascombes, *Flexible Intramedullary Nailing in Children*,
DOI: 10.1007/978-3-642-03031-4_9, © Springer-Verlag Berlin Heidelberg 2010

- Ionizing power of X-rays, that is, the spatial density of ionizations produced in the irradiated tissue. Instead of using the terms "dose equivalent", which may be confusing, one now refers to "weighted radiation dose", which corresponds to the absorbed dose multiplied by a corrective factor (w_R), which takes into account the linear energy transfer (LET). For X-rays used in imaging techniques, this factor is equal to 1:

$$\text{Weighted dose (mGy)} = \text{Absorbed dose (mGy)} \times w_R.$$

- Radiosensitivity of the tissues and organs that are exposed to radiation during the examination. Then, the ED is calculated and expressed in Sievert (Sv) or milliSievert (mSv) to allow evaluation of the radiobiological effects. The ED is proportional to the weighted dose absorbed by each organ or tissue multiplied by a weighting factor (w_T), which varies according to the radiosensitivity of the organ/tissue exposed to radiation (Table 9.1). The sum of all weighting factors (w_T) is equal to 1. In imaging ($w_R = 1$), the ED is equal to:

$$\text{ED(mSv)} = \Sigma_{\text{Tissues, Organs}} \text{ Absorbed dose(mGy)} \times w_T$$

Based on the ED, it is possible to predict the stochastic effects resulting from an X-ray examination. The calculated dose for an examination, which has exposed the patient to a certain amount of radiation is equivalent, in terms of stochastic effect (i.e., probability of cancer/leukemia induction), to exposure of the whole body to the ED.

Based on the values wT presented in Table 9.1, it is easy to classify imaging examinations according to the potential risk of each exam. The more radiosensitive organs exposed to radiation, the higher the risk. Therefore, the ED to a patient during imaging examination of a limb, a joint, or the skull is very low, whereas, the ED delivered during gastrointestinal tract examination, intravenous urography, barium enema examination, and CT scan of chest, abdomen, or pelvis is very high.

Table 9.1 Tissue/organ weighting factors (as per ICRP 60)

Organs	wT
Gonads	0.20
Red bone marrow, colon, lung, stomach	0.12
Breast, bladder, liver, esophagus, thyroid	0.05
Bone surface, skin	0.01
Remainder	0.05
Total	1.00

Example: according to ICRP 60 (International Commission on Radiological Protection No. 60), the total cancer risk for an individual aged between 18 and 65 years is 4.8% per Sievert. Therefore, the chances for an individual to develop cancer after a chest/abdomen/ pelvis CT scan, during which an ED of 10 mSv has been delivered, would be 0.048%.

Now that we have reviewed the deleterious effects of ionizing radiation, we must compare the risks to patients from medical X-rays versus natural background radiation.

According to CEA, "Sixty percent of the average exposure to radiation comes from natural sources."

Natural background radiation comes from three primary sources:

- Cosmic radiation (approx. 0.30 mSv/year at an altitude close to sea level, 1 mSv at an altitude of 2,000 m).
- External terrestrial sources (approx. 0.35 mSv/year in France). In some granitic regions, natural radiation doses are higher.
- Radioactive substances ingested with food/water or inhaled (mean, 1.55 mSv/year).

Tabulation forty percent of the average exposure to radiation comes from human-made sources.

For each individual, the average exposure is about 1 mSv per year. Human-made radiation sources include:

- Medical X-rays: average dose (France) from dental and medical diagnostic X-rays is almost 1 mSv/year.
- Nonnuclear industrial activities: average dose from coal burning, phosphate fertilizers, television, luminous watches is 0.01 mSv/year.
- Nuclear industrial activities: average dose from nuclear power stations, reprocessing plants, fallout from past nuclear tests, and Chernobyl accident etc. is 0.002 mSv/year.

Clearly, medical applications are the main source of human-made radiation, and the only one that can actually be controlled. Therefore, both the patient and the surgeon need appropriate protection, and X-rays should be used advisedly.

9.2 Optimal Use of an Image Intensifier to Minimize Exposure of Both the Patient and the Surgeon to Radiation?

One must distinguish between direct radiation and scattered radiation. Direct radiation is when a specific part of the body is exposed to the primary beam. Direct radiation is useful to obtain an image. Scattered or secondary radiation is highly detrimental because not only does it produce an odd, blurred image, but, more importantly, it exposes the neighboring radiation- sensitive organs, and the surgeon and clinical personnel (Fig. 9.1).

Scattered radiation is created by radiation acting on or passing through matter. Primary scattered radiation is emitted from the patient's organ. Secondary scattered radiation results from interaction of primary scattered radiation with other objects. Here, we shall only discuss the primary scattered radiation.

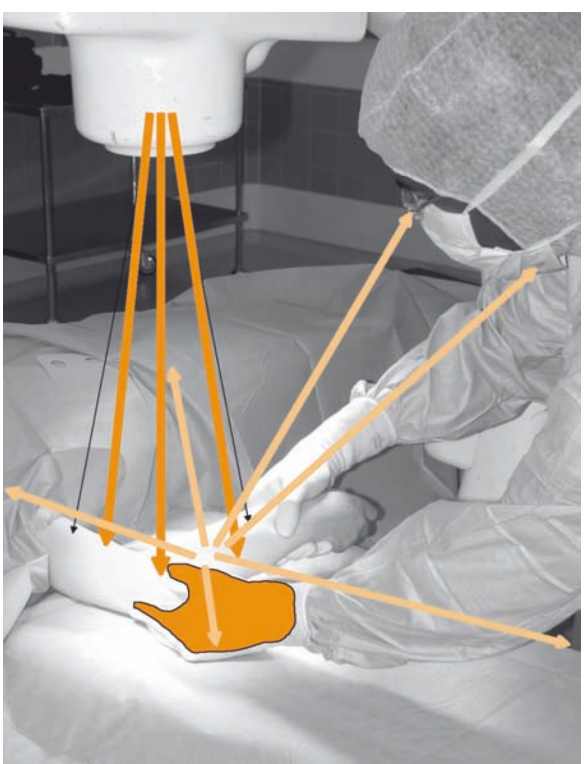

Fig. 9.1 X-ray distribution with fluoroscopy. Scattered radiation (*light color*) Primary radiation (*dark color*)

During fluoroscopy, the patient's fracture site is exposed to direct radiation (primary radiation), and the entire patient's body, and more particularly, the most radiosensitive organs (i.e., gonads, thyroid, lens of the eye, and thymus) are exposed to indirect radiation (secondary radiation). As a rule, the surgeon always keeps hands out of the beam, and is only exposed to secondary radiation due to scattered X-ray beam. The primary dose depends on kilovoltage, milliamperage, and screening time.

Recent fluoroscopic equipment typically adjusts the technique factors (kilovoltage and milliamperage) automatically to provide high-quality images. Screening time is the only variable that can be controlled by the operator to reduce direct radiation.

Secondary radiation is in relation with primary beam intensity, and any measures taken to reduce this intensity will help reduce secondary radiation. However, other parameters related to the use of the image intensifier itself should be taken into account. Optimal use of the image intensifier can lead to the reduction of scattered radiation by a factor of up to ten (or greater).

The amount of scattered radiation further depends on the treatment volume and surface area, and the distance between the X-ray tube and the measurement point (square of the distance from a point source). The radiation source (i.e., X-ray tube) should always be as far as possible from the limb, with the image intensifier tube as close as possible to the injured segment. Practically, secondary radiation can be minimized by:

- Working with lens at minimum aperture.
- Placing the X-ray tube above and the image intensifier beneath the involved limb segment.

To alter the magnification effect, some surgeons use a reverse positioning. This must be proscribed, as it significantly increases scattered radiation and its associated risks for the surgeon and the patient.

If all the constants are optimally adjusted, the X-ray tube properly positioned, and the lens at minimum aperture, scattered radiation is minimized. The child can be protected against residual radiation by covering his/her radiosensitive organs with lead shields. The best way for the surgeon to protect against radiation exposure is to keep as far from the beam as physically possible. When backed away from the tube 2 m, the operator is better protected than with any lead apron [3].

Therefore, instead of compelling all operating room personnel to wear a heavy and uncomfortable lead apron during the whole procedure, it is much preferable to ask any individual, whose presence in the exposed area is not indispensable, to stand at least 2 m away from the X-ray tube.

During initial reduction and passage of the first nail across the fracture site, the surgeon cannot step backwards as reduction must be maintained at all times. Therefore, maximum protection is necessary: lead apron, thyroid collar, and even lead eye glasses. Most important, the surgeon must keep hands out of the beam as much as possible [1, 4], and avoid using soft, flexible lead gloves that can be resterilized, as they do not provide the required level of safety. At a distance of a few centimeters from the beam, hands are only exposed to scattered radiation.

9.3 Prospective Study of the Actual Amount of Exposure Received by the Patient and the Surgeon During a FIN Procedure

Redefine good clinical practices was one thing, but we wanted to evaluate the actual dose received by the patient and the surgeon during a FIN procedure.

9.3.1 Materials and Methods

During the second half of 2005, we measured the doses received by patients and surgeons during 13 FIN procedures. We developed a measurement protocol. For each patient, the following baseline data were recorded: age, height, weight, fracture location, name of surgeon, radiation parameters (i.e., kilovoltage, milliamperage, screening time). For each procedure, we measured the radiation dose delivered to the patient using three dosimeters placed over gonads, thyroid, and at the root of the limb. We placed a detector at the left wrist of the surgeon, inside the glove.

We routinely used two image intensifiers, as well as a stenoscope (General Electric Medical System) and a Siramobil® (Siemens), both delivering a high voltage of between 40–50 and 100–110 kV, and a current of between 0.3 and 4.5 mA. The dose rate to image intensifiers was measured at a distance of 750 mm from the radiation source using a PMX III® multimeter (RTI Electronics AB), calibrated to the used kVp values and for a W/W anode/filtration combination. The 750 mm reference distance corresponds (in accordance with good clinical practices) to the distance between the operated limb and the radiation source during the procedure. The radiation dose to the patient from the reference distance of 750 mm was calculated based on the parameters used for each procedure (i.e., kV, mA, and screening time).

The dose received by the patient and the surgeon was measured using radiothermoluminescent (RTL) dosimeters. The Harshaw TLD-700® Lithium fluoride (LiF) dosimeters contained chips with dimensions of 3.175 × 3.175 mm and 0.9 mm thickness. Dosimeters were processed with a 2,000D® automatic reader coupled to a Harshaw 2,000B® integrating picoameter for thermoluminescence reading.

All RTL dosimeters had equal sensitivity to within ±5 %. In compliance with the defined protocol, we used two detectors per measurement point, which allowed us to obtain accurate measurements to within ±3.7% with a confidence interval (CI) of 95%. We selected to use cobalt-60 irradiation for calibration because it was readily available in the Radiotherapy Department of the Center Alexis-Vautrin, Nancy, and also because beam is more stable. Due to the enhanced response of LiF dosimeters at low energies, within the used kVp range (40–60 kV), the response had to be corrected by a factor of 1.30 [5]. Our sensitivity threshold is estimated at 0.5 mGy, which corresponds to the lowest dose recorded.

9.3.2 Results

Dosimeters were placed and radiation exposure measured in 13 patients treated by four different surgeons: two Associate Professors/Hospital Practitioners, one full-time Hospital Practitioner, and one Senior Registrar. Mean age of the patients was 7.9 years (range, 3–15 years), and mean weight 26.9 kg (range, 15–53 kg). Fracture locations included: femur (6) including one femoral neck (in the area of a bone cyst), elbow (5), forearm (2). The dose rates to image intensifiers being uniform to within ±10%, they were grouped together; variations in mean dose rate according to kVp at the reference distance of 750 mm are presented in Fig. 9.2.

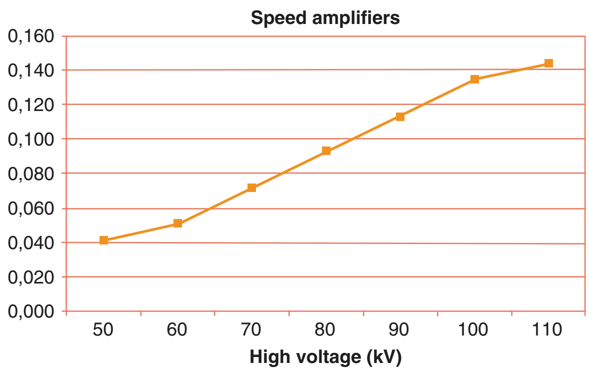

Fig. 9.2 Variations in mean dose rate (mGy/mA) to image intensifiers as measured at the reference distance of 750 mm from the radiation source

Fluoroscopy parameters included high voltage, 48–61 kV; current, 0.3–1.8 mA; screening time, 0.2–4.0 min. The radiation dose delivered under these conditions at the reference distance of 750 mm ranged from 0.8 mGy to 11.3 mGy. In the whole series, mean values per procedure were 54 kV, 111 mA, for a dose of 5.0 mGy at a distance of 750 mm from the radiation source.

All measurements are presented in Table 9.2. Mean doses measured in patients were: 0.6 mGy in gonads (range, 0.5–2.0 mGy), 0.5 mGy in thyroid (sensitivity threshold), 1.0 mGy (range, 0.5–5.0 mGy) at the root of the limb. Mean dose measured at the surgeon's wrist was 0.6 mGy (range, 0.5–1.0 mGy).

9.3.3 Discussion

Radiation doses are very low; many estimated values are under 0.5 mGy, which was the threshold value in our measurement method. But overall, values at the root of the limb are significantly higher: 6 out of 13 exceeded 0.5 mGy, and 1 reached up to 5 mGy (2 mGy to gonads) in treatment of a complex femoral fracture.

Surgeons must bear in mind that for fractures located close to the root of a limb, and more particularly, femoral fractures, screening time must be kept to a minimum.

The amount of exposure received by the child during a single FIN procedure is relatively low even for a complex fracture, and it is very reassuring, indeed.

As regards surgeons, the doses involved are also very low, since 10 out of 13 are lower than or equal to 0.5 mGy, even in technically demanding procedures. However, one must consider the fact that pediatric orthopedic surgeons perform a lot of FIN procedures plus many other procedures, which require the use of an image intensifier.

Therefore, while not getting alarmed, every surgeon should be aware of this risk, and take appropriate measures to reduce it as much as possible. First of all, the operator should always keep hands out of the beam and work with lens at minimum aperture. No one would have the silly idea of putting hands in the fire; this also applies to the X-ray beam. The surgeon should maximize distance, whenever possible, to protect against scattered radiation, which rapidly decreases to become

Table 9.2 Radiation doses measured during flexible intramedullary nailing (FIN) procedures in gonads, thyroid, and at the root of the limb for patients and at the wrist for surgeons, using radiothermoluminescent (RTL) dosimeters (mGy)

Doses (mGy)	Gonads	Thyroid	Root of limb	Surgeon's wrist
Patient 1	0.5	0.5	0.5	0.5
Patient 2	0.5	0.5	0.5	0.5
Patient 3	0.5	0.5	2.0	0.5
Patient 4	0.5	0.5	1.0	0.5
Patient 5	0.5	0.5	0.5	0.5
Patient 6	0.5	0.5	0.5	0.5
Patient 7	2.0	0.5	5.0	0.5
Patient 8	0.5	0.5	0.7	1.0
Patient 9	0.5	0.5	0.5	0.5
Patient 10	0.6	0.5	0.6	0.6
Patient 11	0.5	0.5	0.5	0.5
Patient 12	0.5	0.5	0.6	0.6
Patient 13	0.5	0.5	0.5	0.5
Mean dose (mGy)	0.67	0.5	1.02	0.6

nil at a distance of 2 m. This precaution, yet essential, is too often ignored, probably because surgeons fear that aseptic conditions are not ensured.

9.4 Conclusion

Everyone in the orthopedic community agrees that FIN is a high-performing, effective technique. It further carries a low risk of radiation exposure to the patient and the surgeon, as long as image intensification is properly used and screening time is kept to a minimum. Although the risk for the surgeon is very low, radiation exposure may become significant over a surgeon's career. Therefore, surgeons must be aware of this, and take preventive measures.

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10 Rehabilitation After FIN

Claude Gavillot and Francine Rumeau

10.1 Specificity of Limb Fractures in Children and Benefits of FIN

Whatever the technique used, there are less indications for trauma rehabilitation in children than in adults. The reason is that children naturally make movements, which contribute to rehabilitation. Even after prolonged immobilization, joint stiffness remains a rare complication that is only seen in special cases such as articular fractures, associated injuries, bone weakness, neuromuscular diseases, etc. Likewise, physical therapy is seldom needed for muscle strengthening, as the spontaneous activity of children is generally sufficient to allow good functional recovery.

Flexible intramedullary nailing (FIN) is essentially performed in children aged between 6 and 14 years [1, 2]. Stability provided by FIN is such that adjunctive immobilization is often unnecessary. Thus, children usually recover a full range of motion, naturally. As no bed immobilization is needed, time lost from school is minimized, and the psychological impact of prolonged hospitalization is reduced.

In multiply injured children, the absence of immobilization greatly facilitates nursing care, assessment of local condition, resuscitation care, additional examinations, and inter-unit transfers. Postoperatively, three situations are generally met [3]:

- The child moves his/her operated limb early and spontaneously and rapidly recovers full range of motion: no rehabilitation is necessary.
- The child is somewhat apprehensive and avoids moving his/her operated limb: some rehabilitation is necessary during hospital stay, consisting in confidence- building sessions, teaching of crutch walking, restoration of voluntary muscle activation, etc.
- In rare instances, complications, associated injuries, or specific patient's conditions are encountered: in this case, the child needs prolonged physical therapy first in hospital stay, and after discharge, in an individual physical therapist's practice.

10.2 Rehabilitation After Upper Limb Fracture Management

The child wears a simple sling for about 3 weeks during activities. The sling is mainly intended to protect the child on his/her return to school by inciting other children to be more careful. Nevertheless, self-mobilization is highly encouraged.

In supracondylar humeral fractures [4], extension lag is frequent during the first postoperative weeks, and generally improves spontaneously within a few weeks. If not, a few physical therapy sessions are prescribed to perform active and active-assistive exercises. Forced passive, painful stretch is proscribed, as well as massages, which may promote the development of osteoma of the brachialis muscle. Should the flexion contracture persist longer than 3 months post surgery, a static elbow extension orthosis or a dynamic elbow extender (i.e., three-point pressure system) will be used after each physiotherapy session, and during the night.

Adequate reduction of forearm fractures in all planes should normally allow recovery of full range of pronation–supination. Immediately after surgery, range of motion may be restricted due to pain and postoperative edema, but the child usually recovers the full range of motion, gradually and spontaneously. However, should functional impairment persist, the root cause will have to be investigated, both clinically and radiographically, to

P. Lascombes, *Flexible Intramedullary Nailing in Children,*
DOI: 10.1007/978-3-642-03031-4_10,© Springer-Verlag Berlin Heidelberg 2010

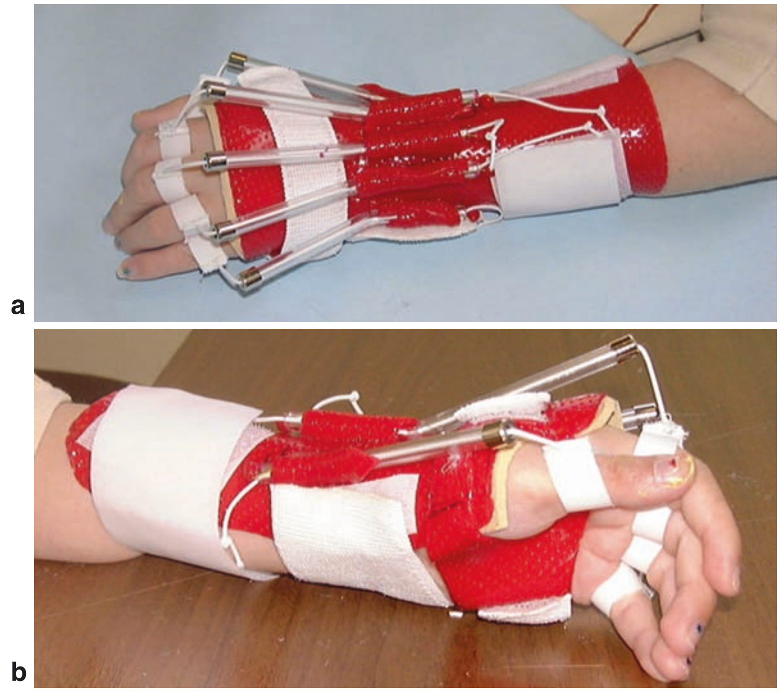

Fig. 10.1 Orfitube system used for radial nerve palsy (a, b)

determine whether physical therapy would be both appropriate and beneficial. The presence of a bony block is a contraindication to the use of any stretching technique, whereas contracture and retraction of muscles or capsuloligamentous structures can be managed with physical therapy.

Early rehabilitation is justified in the presence of associated injuries or complications. In case of radial nerve palsy, active extension deficit at the wrist can be compensated by a stabilizing wrist orthosis, which will prevent the development of a swan neck deformity. This orthosis should be worn during daytime activities, as long as the motor deficit is present (Fig. 10.1). If necessary, a finger extension assist can be used in combination with the orthosis. Median nerve palsy can be easily managed with finger mobilization to maintain good range of motion, as recovery is often quick. A specific form of median nerve palsy involves the anterior interosseous branch of the nerve (AIN), and is manifested by loss of active flexion of the interphalangeal joint of the thumb and distal interphalangeal joint of the index finger. In case of ulnar nerve palsy, clawing of ring finger and little finger may require, in addition to joint mobilization, the use of a Zancolli type anticlaw splint (Fig. 10.2).

Fig. 10.2 Zancolli anticlaw splint for median-ulnar nerve palsy

Compartment syndrome leads to complications such as trophic changes and muscle retractions. If very severe, muscle retractions will require prolonged rehabilitation combining appropriate physical therapy and dedicated assistive products. Children with uncomplicated upper limb fractures can return to sports early with the nails in situ. However, after nail removal, that is, at 3 months for humeral fractures and after the sixth month for forearm fractures, the child must again refrain from sports for a few weeks.

10.3 Rehabilitation After Lower Limb Fracture Management

Most of the time, immobilization consists in the application of a compressive dressing to the knee joint for a few days, after which unrestricted motion is allowed.

However, after FIN of the femur, quadriceps inhibition often occurs, and the child rapidly adopts an antalgic posture with the knee flexed. A few physical therapy sessions are then necessary to remove the inhibition and restore full extension against gravity. The child must succeed in lifting the leg off the bed with the knee fully extended. Failure of voluntary activation of the vastus medialis often persists, whereas voluntary force is fully recovered in other quadriceps muscle heads. Instructions about correct positions while in bed or in armchair are important to prevent the development of a fixed flexion contracture, which may occur as long as voluntary quadriceps activation has not been restored. Existing techniques for relieving muscle contractures can be most helpful. It is important to help the child build confidence by explaining that healing is well under way, and that his/her bone is already very strong. As a matter of fact, many patients think that if they move, they will again feel instability in their femur as after their accident. Knee flexion exercises are not recommended, as they may increase the risk of skin impingement at nail ends, which would necessitate reoperation for nail trimming. Physical therapy for knee inflammation and knee pain uses ice, cold therapy [5].

Once active extension against gravity is recovered, the child is allowed up. A 7-year-old child readily learns how to walk with two crutches, without putting weight on the injured leg. Rapid bone healing allows full loading of the fracture site as soon as sufficient external callus has developed, that is, at 3 weeks for transverse fractures and 6 weeks for other fracture patterns. The importance of gradual resumption of weight bearing is one thing, but it is another thing to explain the notion of "partial weight bearing" to a child less than 10 years old.

Most of the time, the rehabilitation program only includes, initial recommendations, instructions on how to move and change positions in bed, and teaching crutch walking.

After removal of hardware around the fourth postoperative month, the patient gradually recovers full flexion.

After FIN of the tibia, immobilization in a cast boot is often necessary to achieve correct alignment. In any case, active mobilization of knee, foot, and toes should be encouraged so that the child can rapidly lift his/her leg off the bed. As regards resumption of weight bearing, the rules mentioned for femur also apply to tibia.

Children with uncomplicated tibial fractures can return to sports 4 months after surgery. However, after removal of hardware, the child must again refrain from sports for a few weeks to avoid the risk of fracture at nail entry sites where bone is weaker.

Complex tibial fractures, crush injuries, and ipsilateral fractures of the femur and tibia may be associated with neurovascular complications and compartment syndrome, as is the case in adults. Therefore, prolonged rehabilitation using an individualized protocol is desirable to meet the patient's needs: joint stiffness, muscle retractions, sensorimotor deficit, etc. In case of paralysis of the dorsiflexors, a foot drop brace is immediately applied to prevent the development of equinus posturing (Fig. 10.3). Resumption of weight bearing is allowed with a protective ankle foot orthosis (AFO) (generally from a special thermoformed material). In the presence of sensory disorders, appropriate footwear should be used to avoid skin lesions. Molded inserts for pressure distribution may be prescribed, if necessary.

Fig. 10.3 In case of paralysis of the dorsiflexors, a foot drop brace is immediately applied to prevent the development of equinus posturing

10.4 Specific Conditions

In children with osteogenesis imperfecta [6, 7], sliding FIN provides effective stabilization of the fracture while offering long-term protection. Nails need replacement during the growth period. In severe cases, sliding nailing is effective in preventing both long bone fractures and bone deformities. Quick recovery of physical independence provided by sliding FIN is of paramount importance in children who may have multiple fractures. In severe forms of the disease, angular deformities and joint stiffness are frequent. Having a lower spontaneous muscle activity, these children do not spontaneously recover full range of motion. Therefore, it is essential that rehabilitation is started early in order to try and maintain maximum range of motion and minimize amyotrophy. The absence of external immobilization and early resumption of weight bearing are most beneficial to children in whom maintenance of functional capacity is crucial. In severe cases, referral to a rehabilitation center may be considered.

In children with cerebral palsy or neuromuscular disease (i.e., myopathy, spinal amyotrophy, spina bifida, paraplegia, quadriplegia, etc.), immobilization and conservative treatment are badly tolerated. As a matter of fact, these children are at high risk of skin complications and functional impairment with loss of walking or sitting ability, which may lead to respiratory complications and threaten the vital prognosis. FIN promotes rapid healing and makes external immobilization unnecessary, thus allowing the patient to quickly resume the sitting position. The nails are left in situ to provide a permanent supportive frame. Early postoperative rehabilitation is essential for many reasons: poor motor capacity, and increased risk of pressure sores or joint stiffness with fixed angular deformities.

10.5 Algodystrophy or Complex Regional Pain Syndrome Type 1

Although uncommon in children, this complication must be recognized by the surgeon. It may occur after FIN, such as after any orthopedic procedure or some form of disturbance like immobilization. The causative mechanisms are complex and involve the sympathetic system. Complex regional pain syndrome type 1 (CRPS 1) (according to the international association for the study of pain [IASP, 1993]) was formerly termed "reflex sympathetic dystrophy" (RSD) [8–12].

Pediatric CRPS 1 affects mainly the lower limbs with a predilection for the foot and ankle, and occurs predominantly in girls (70%).

Although clinical picture is sometimes nonspecific, unexplained pain associated with trophic and vasomotor changes are evocative of this condition. Cold-type CRPS 1 is common in children, and combines spontaneous and/or mechanically evoked pain (i.e., hyperalgesia and/or allodynia), hypothermia, and cyanosis. Standard radiographs are normal in 70% of the patients with no signs of demineralization. Decreased uptake on bone scintigraphy is noted in 60% of the patients.

In patients, where motion and weight bearing elicit excruciating pain, there is total loss of function. The psychological aspect must not be overlooked. The various studies conducted in adult patients did not show a unique psychological pattern in patients with CRPS 1, but emphasis has been placed on the importance of posttraumatic stress and therefore, on the necessity of informing and reassuring the patient. As far as children are concerned, many authors report a significant parental enmeshment with the child, frequent parentchild conflicts, and excessive somatization.

Once diagnosis is established, management should preferably be initiated in the hospital. Rehabilitation is the mainstay of CRPS 1 treatment. It should be started as early as possible, and be strictly pain free. It mainly consists of: hydrotherapy, physical therapy, transcutaneous electrical nerve stimulation (TENS), active and active-assistive range of motion exercises, and muscle strengthening by open chain kinetic exercises (OKCE). In cases, where the lower limb is involved, the patient is not systematically kept off weight bearing. The use of walking aids may be preferable to allow protected weight bearing and maintain a good gait pattern.

The aim of pain medications is to provide sufficient pain relief to allow effective participation in physical therapy. Pain should be priorily evaluated using a visual analog scale (VAS) or a numerical scale (NS): pain at rest, and above all, pain with motion, in order to give appropriate medications. Nociceptive pain is managed with class two or three analgesics. Neuropathic pain is managed with tricyclic antidepressants, if continuous: amitriptyline or clomipramine (intended for adult use, according to the summary of product characteristics [SPC]), or with anticonvulsants, if paroxystic (e.g., clonazepam, gabapentin). The effectiveness of calcitonin is questionable, more especially, as it is only available as injections (which are badly tolerated in these patients), and are intended for use in patients over the age of 18 (according to SPC). However, it is sometimes used in warm-type CRPS 1, which rarely occurs in children. In case of failure of the above-mentioned treatments, nerve blocks may be considered: perineural ropivacaine 0.2% and/ or intraneural injection of 1.0% lidocaine combined with buflomedil (which, according to SPC, is normally not intended for use in children). Nerve block provides adequate analgesia to perform mobilizations [13].

The multidisciplinary approach is effective in providing pain relief, thus allowing early recovery of range of motion and resumption of weight bearing. In CRPS 1, the neuropathic and psychological components of pain should systematically be taken into account. Psychotherapy is often used as adjunctive treatment to assist coping. Severe recurrent bouts of CRPS sometimes occur, but on the whole, children respond favorably to treatment. Again, the preventive role of good quality posttraumatic and postoperative analgesia must be emphasized.

10.6 Conclusion

Spontaneous recovery of full range of motion is consistently observed after FIN. In simple fractures, rehabilitation does not play an important role: it just helps the child to rapidly recover full independence. However, in patients with associated injuries or complications, which may result in functional impairment, rehabilitation is necessary.

FIN is particularly well suited for children who poorly tolerate nonoperative treatments and prolonged immobilization: it carries a very low risk of cutaneous and orthopedic complications, and has a low potential for functional impairment, which may sometimes be life threatening.

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11 Professional Caregivers' Perspective

Marie-Christine Mirouf

11.1 Introduction

With the exception of multiply injured patients who are directly admitted to the resuscitation unit or even the operating room, a child with an isolated bone fracture generally arrives in the emergency department, where initial care is given (i.e., immobilization, analgesics, regional nerve block if needed), before being transferred to the Department of Pediatric Orthopedics.

11.2 Admission Practices in Hospitals

Hospital admission is emotionally disturbing and may significantly impact the child's hospital stay. As trauma hospitalization is due to an undersigned, sudden, and unexpected event, it has not been prepared and organized, contrary to a scheduled hospitalization for elective surgery. It makes it a stressful experience for the parents, and above all, for the child who sometimes discovers a yet unknown world.

Whether or not accompanied by the parents, the child is taken to an individual or multiple-bed room. Information about the healthcare team is given to the parents and/or the patient. The data needed for the child's care is collected: medical data (i.e., medical/surgical history, known allergies, etc.), child's routines, likes and dislikes, family environment. This helps caregivers meet the individual needs of the patient.

Except in emergency situations, surgery is performed when the patient has a completely empty stomach. This may leave enough time for the team to learn more about the child and prepare him/her for the procedure by viewing a videotape depicting the operating room, as one must not forget that fear is typically associated with the unknown. A caregiver describes different steps of the procedure in simple words, and the child is free to ask questions to the surgical team. These exchanges are vitally important to dissipate anxiety, and are adapted to the age and maturity of the child.

11.3 Back from the Operating Room

The personnel must be prepared to answer parents' frequently asked questions, after the procedure and throughout the child's stay. Parents are generally surprised by the absence of splinting, and are a bit worried to learn that their child is authorized to move his/her fractured limb. They are also very often impressed by the size of edema. It is the role of care providers to reassure both the child and the parents, and to answer questions such as:

- Is my child not going to wear a cast?
- Can he/she move freely?
- When should the dressing be replaced?
- What about taking a shower or a bath?
- Will he/she need rehabilitation?
- When can ambulation be resumed?
- Will he/she need crutches or a wheelchair?
- Will the nails be removed? When? Will general anesthesia be necessary?

Fractures managed with flexible intramedullary nailing (FIN) require both routine monitoring and specific monitoring. The child is taken back to the orthopedic department after a short stay in the post anesthetic care unit (PACU recovery room).

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DOI: 10.1007/978-3-642-03031-4_11,

11.3.1 Routine Monitoring

Routine monitoring includes:

- Monitoring of central hemodynamic parameters (i.e., pulse, blood pressure, temperature, etc.) after surgery, every 2–3 h according to instructions.
- Monitoring of peripheral venous access, which is maintained for administration of analgesics.
- Gradual resumption of diet as prescribed by the anesthesiologist. If vomiting occurs, it can be easily controlled by intravenous antiemetics.
- Evaluation of pain intensity using appropriate tools.
  - Self-evaluation by children more than 6 years old using a visual analog scale (VAS).
  - Observational evaluation in children less than 6 years old.

Objective measures must be used as pain threshold varies from one individual to another. Special attention should be paid to certain fractures, which are notoriously more painful such as femoral fractures or supracondylar humeral fractures. Dosage of analgesics is based on pain assessment results.

The emotional component of pain is an important factor that must be taken into account. However, any local pain that fails to respond to analgesics should suggest a complication (often a compartment syndrome).

11.3.2 Specific Monitoring

Proper in-bed positioning is important both for patient comfort and for pain management, and helps minimize the development of postoperative oedema.

For upper limb fractures, the child is positioned supine or in the beach-chair position with the arm elevated on 1–2 pillows.

For lower limb fractures, the child is positioned supine:

- The leg is elevated on 1–2 pillows.
- A gel cushion is placed under the buttocks for the first 48 postoperative hours because of restricted motion.
- A sand bag is placed on each side of the leg to maintain axial alignment and prevent external rotation.
- A bed blanket support is systematically used to eliminate the weight of blankets.

11.3.3 Local Monitoring

Local monitoring is mainly focused on the detection of compartment syndrome: assessment of warmth, skin color, motor or sensory function in the limb and all extremities. Disappearance of distal pulses and onset of sensory loss are indicative of a vascular and/or nerve injury. More importantly, persistence of abnormal pain in the forearm or the leg, and loss of active motion and even passive motion in fingers or toes and foot must be promptly reported to the surgeon.

The child must be encouraged to perform simple movements to test the motor power of his/her limb and extremities. A child is often reluctant to do so because of the fear of arousing pain or causing displacement of the fracture. Here again, it is the role/responsibility of the caregivers to help the child build his/her confidence.

11.3.4 Oedema Monitoring

Oedema is inevitable and may vary in size. Evaluation of oedema resolution is mandatory (e.g., by measuring the circumference of the thigh) because oedema may cause skin damage that will require specific care.

11.4 Immediate Postoperative Period

11.4.1 Physical Therapy

For femoral fractures, physical therapy is started on the first postoperative day. A precise schedule must be set to ensure that analgesics are given 30 min before each session. Pain control is indispensable to facilitate rehabilitation; this requires perfect coordination between the physical therapist and caregivers. Although the rehabilitation period is generally short, it often proves most effective in prompting the child to rapidly mobilize his/her limb.

11.4.2 Getting Out of Bed

The child is allowed up:

- Upper limb fractures: on the first postoperative day, with the arm in a sling. It is extremely important to get the child to understand the importance of keeping the hand elevated.
- Lower limb fractures: on the second or third post operative day, depending on the child's clinical condition. As a matter of fact, the child must be able to lift the leg off the bed prior to ambulating with two crutches (without bearing weight on the operated leg).

11.4.3 Wound Care

Dressing is changed on day 1 or day 2. The initial compressive dressing is replaced by a water-tight dressing, which allows the child to take a shower; baths should be avoided for about 10 days, until full healing has occurred.

11.5 Hospital Discharge

The child is discharged from hospital on day 2 or 3 for an upper limb fracture, and around day 6 or 8 for an isolated or uncomplicated lower limb fracture. Prior to discharge, the parents should buy crutches and/or hire a wheelchair if the child is very young. All discharge forms are prepared (i.e., doctor's certificate for exemption from sports/physical education, first follow-up appointment, etc.). A discharge plan for aftercare treatment should be made with the family and the therapist. Potential difficulties should be discussed, as well as conditions of return to school. Social environment should not be neglected; if necessary, caregivers may request the Area Medical Officer or Public Health Nurses to provide advice to parents.

The parents should receive the necessary instructions regarding home care, and more particularly: temperature monitoring to detect any sign of infection as for any implanted device; careful inspection of scars to detect for possible nail prominence or even nail protrusion through the skin. Additional instructions include: child's limb elevation, administration of analgesics, physical therapy (where necessary). As a rule, the first follow-up appointment for clinical and radiographic assessment is scheduled within the first postoperative month. However, the parents are instructed to contact the surgeon as soon as possible if any postoperative anomaly is noted.

11.6 Conclusion

FIN greatly facilitates postoperative monitoring and nursing care. The short hospital stay minimizes the psychological impact. The absence of external immobilization allows quick recovery of physical independence to perform routine activities and get around. Time lost from school is only a few days, and the child can rapidly resume sports activities. However, a new hospitalization is necessary for removal of hardware under general anesthesia.

Part II

Technique

12 Fracture of the Proximal Humerus

Pierre Journeau and Pierre Lascombes

12.1 General

The flexible intramedullary nailing (FIN) technique used for the treatment of fractures of the proximal humerus is an adaptation of the Hacketal method used in adults [1]. This metaphyseal fracture is most often stabilized by two unipolar retrograde tapered nails introduced proximal to the lateral epicondyle and anchored in the humeral head.

12.1.1 Epidemiology

Injuries of the proximal humerus, which include humeral neck fractures, and physeal injuries are among the less common injuries of childhood (only 3% of all pediatric fractures). They affect children and adolescents of all ages because the proximal humeral physis is one of the last to close; this explains why physeal injuries occur even in late adolescence. Metaphyseal fractures occur essentially during the first decade of life, whereas growth plate injuries are predominantly seen in adolescents. The proximal humerus owes its exceptional remodeling capacity to its high growth potential, which represents 80% of the total growth of the bone [2].

Metaphyseal fractures are much more frequent than physeal injuries since they account for 70% of all fractures of the proximal humerus. Both types of injuries are essentially due to high-energy trauma.

12.1.2 Mechanisms of Injury and Classifications

These injuries are sustained during athletic activities, road-traffic accidents, and falls from a height. A similar mechanism of injury is identified in all cases: most often, a fall on the outstretched arm, typically, a backward fall with landing on the hand.

As this area is that of capsule insertion and numerous muscle attachments to the proximal humerus, medial displacement of the proximal fragment is generally observed both in metaphyseal fractures and physeal injuries (Fig. 12.1). Valgus displacement occurs only in rare cases whereas the fracture line is located distal to the insertion of the pectoralis major.

In physeal injuries, the junction is located at the medial insertion of the capsule onto the metaphysis. This is why Salter Type II fractures with a posteromedial fragment are commonly seen (Fig. 12.2), Type I fractures are occasionally seen (Fig. 12.3), and Types III and IV fractures are very exceptional [3]. Birth trauma is another type of injury, which generally has a good prognosis and does not require surgery.

The Neer classification system is based on the degree of separation of the epiphysis from the shaft, irrespective of the type injury (i.e., fracture or epiphyseal separation) [4]. Grade I: undisplaced or minimally displaced; Grade II: displacement up to 1/3 width of the shaft; Grade III: displacement between 1/3 and 2/3 width of the shaft; Grade IV: more than 2/3 width of the shaft.

P. Lascombes, *Flexible Intramedullary Nailing in Children*,
DOI: 10.1007/978-3-642-03031-4_12, © Springer-Verlag Berlin Heidelberg 2010

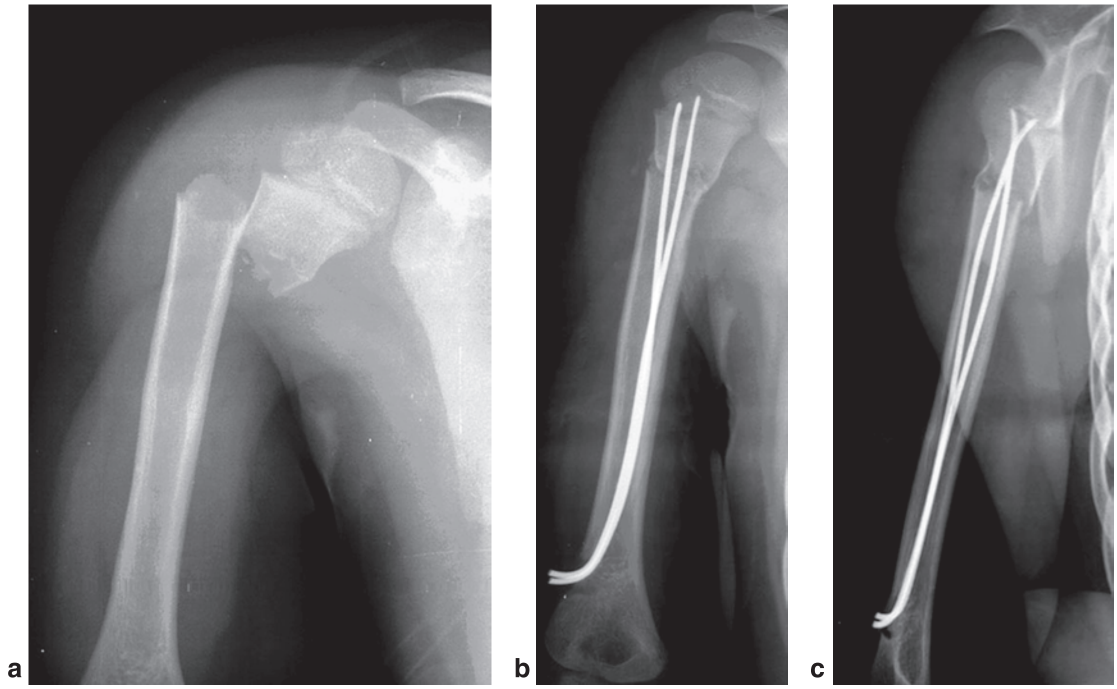


Fig. 12.1 A 3-year-old boy hit by a car, with multiple injuries including a metaphyseal fracture of the proximal humerus (**a**). Flexible intramedullary nailing (FIN) was performed using two 2 mm titanium nails (**b**, **c**)

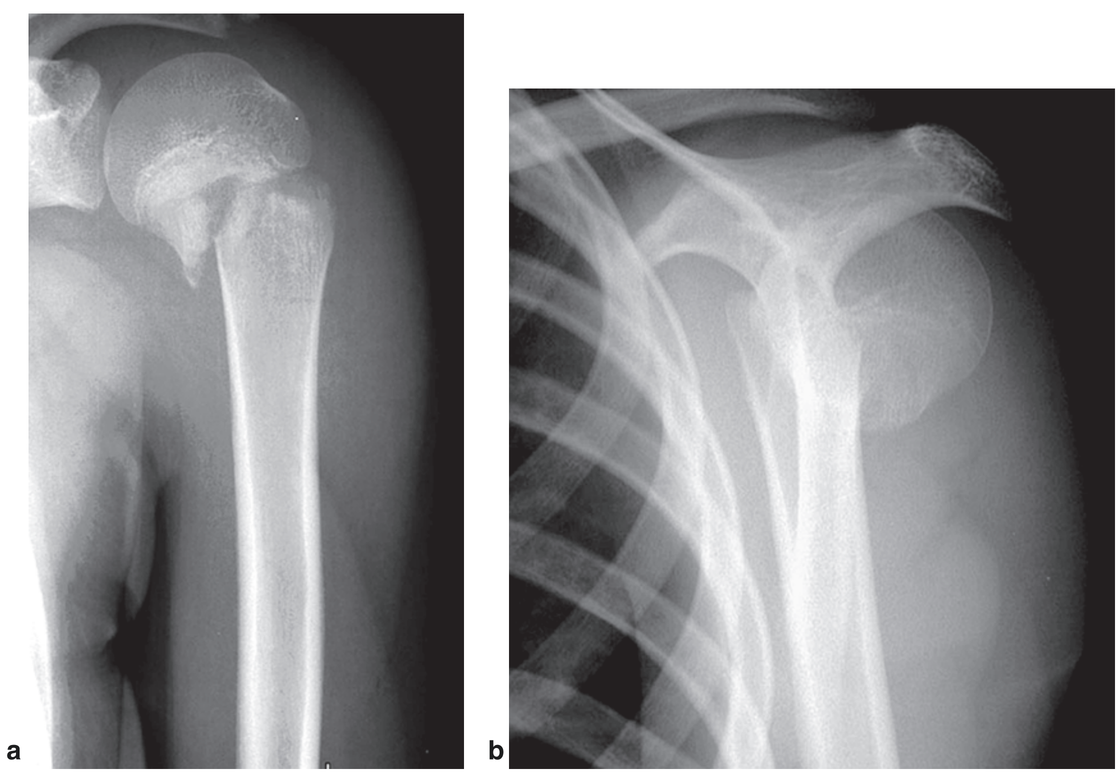


Fig. 12.2 An 11-year-old girl who fell directly on her shoulder stump and presented with a Salter II fracture of the proximal humerus and sensory disorders in the axillary nerve territory (**a**, **b**)

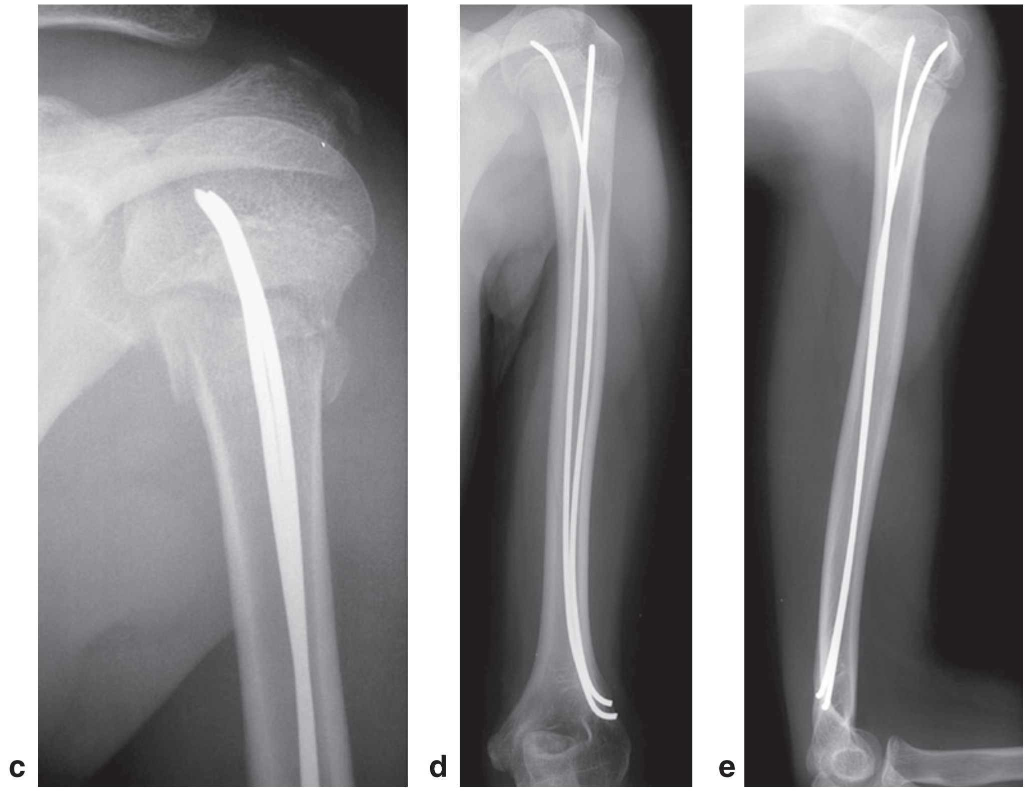


Fig. 12.2 (*cont.*) This fracture was reduced under general anesthesia and treated by unipolar retrograde FIN using two 2.2 mm nails (**c**). Three months later, function was excellent and the nails could be removed (**d**, **e**)

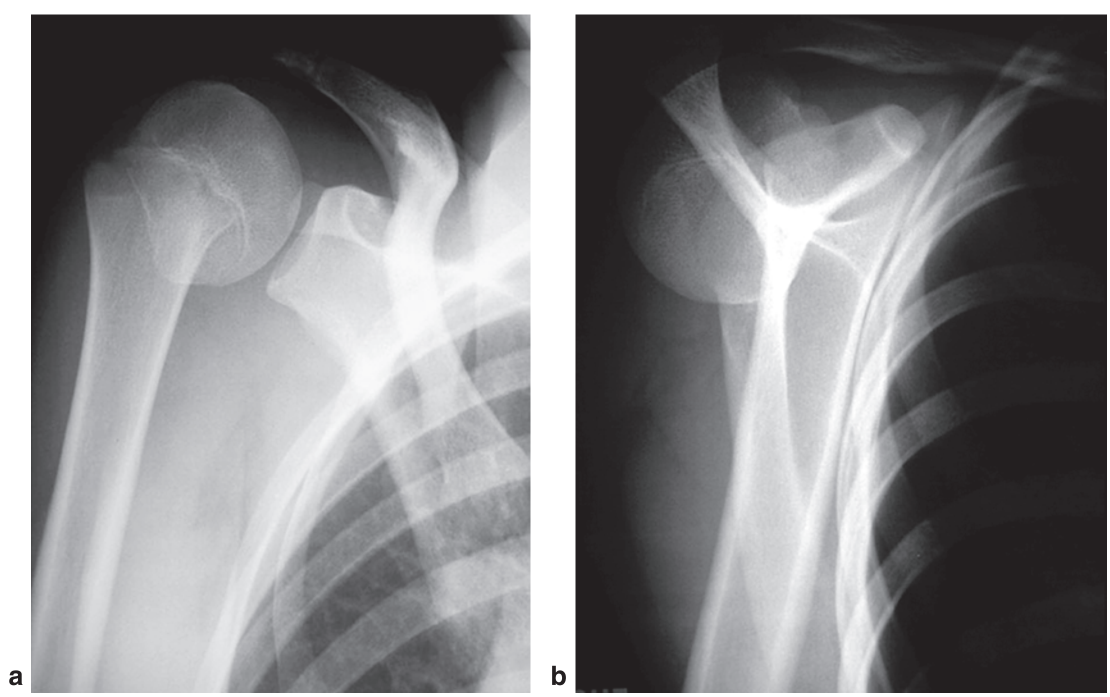


Fig. 12.3 A 13-year-old girl with a Salter I fracture of the proximal humerus sustained during a road traffic accident (**a**, **b**)

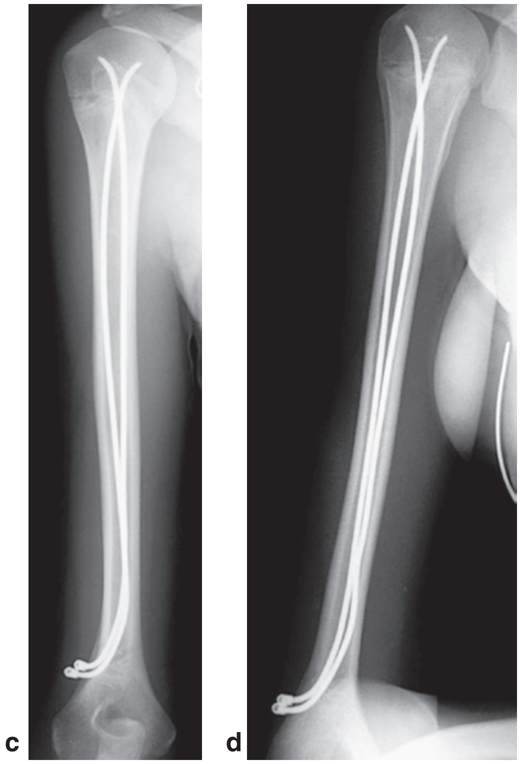


Fig. 12.3 (*cont.*) Unipolar retrograde FIN was performed using two 2.5 mm titanium nails. Titanium end caps were used over the distal ends of the nails. Excellent bone union was achieved at 3 months (**c**, **d**)

As the Neer system does not take the child's age into account, it ignores completely the remodeling potential, which must be considered to establish the indication. Beaty was the one who defined reduction indications for different age groups, based on the amount of displacement and angulation, and on the remaining growth potential [5], whatever the immobilization or fixation method used:

- Up to 5 years old: more than 100% displacement and/or more than 70° of varus angulation.
- Five to twelve years old: between 40 and 70° of varus angulation. Considering the wide range proposed by the author, the amount of angulation (and displacement) is a matter of individual professional judgment, taking into account the age of the child.
- More than 12 years old: more than 50% displacement and/or more than 40° of varus angulation.

12.2 Retrograde FIN Technique

The case we are presenting here is a Salter II physeal injury of the proximal humerus with varus displacement in an adolescent [6, 7].

12.2.1 Anesthesia

General anesthesia is mandatory. As a matter of fact, plexus block is generally ineffective in providing adequate analgesia and complete muscle relaxation of the shoulder stump.

12.2.2 Patient Positioning

The child is positioned supine on the operating table, with the affected upper limb placed on a radiolucent arm table. The patient should be positioned as close as possible to the edge of the table or even in a slightly oblique position to allow good visualization of the shoulder with fluoroscopy. Placement of a tourniquet is not only unnecessary but also impracticable. In some challenging reduction cases, the adolescent is positioned in lateral decubitus, with the arm placed on an elevated arm support for vertical traction.

12.2.3 Image Intensifier

Image intensification is indispensable to assess fracture reduction and check correct nail position. As the fracture site is far away from the entry holes, after draping, the image intensifier is placed at the level of the humeral head, over the axilla, parallel to the operating table, and perpendicular to the arm table. In this position, there is no risk of interference with nail insertion and reduction maneuvers. Sometimes, two image intensifiers are used conjointly to obtain two orthogonal views without moving the limb. With the patient in the lateral decubitus position, the two orthogonal views can be obtained by placing the C-arm in the horizontal plane so that it can be rotated around the shoulder (Fig. 12.4).

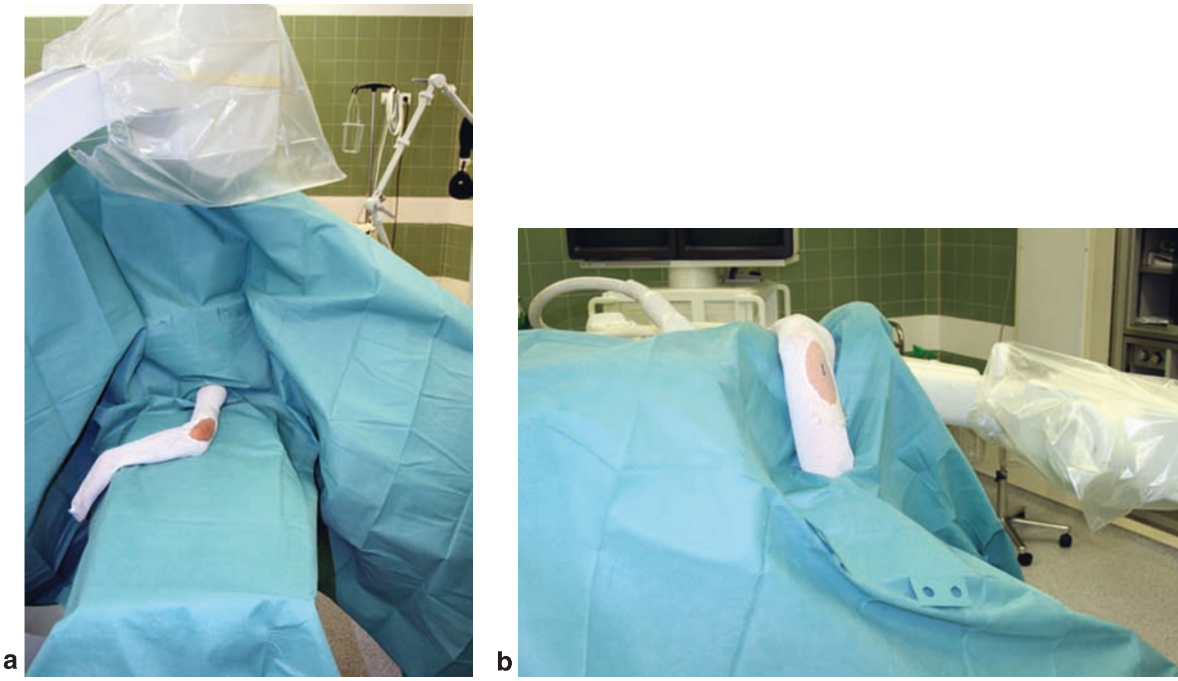


Fig. 12.4 Supine positioning and use of two image intensifiers (**a**), or lateral decubitus positioning with vertical traction applied to the arm and use of one image intensifier in the horizontal plane (**b**). Note the skin incision located in the lateral supra-epicondylar area

12.2.4 Operative Field

The whole upper limb is sterile prepped up to the axilla (including the shoulder), as full mobilization of the arm and forearm will be necessary to perform reduction maneuvers and to access the fracture site from a deltopectoral approach (if necessary). A sterile shoulder drape (U-shape) can be used that covers the arm table, the patient's trunk, and the lower limbs.

12.2.5 Selection and Preparation of the Implants

Sharp or tapered stainless steel or titanium nails must be used because only a pointed nail can penetrate the dense epiphyseal-metaphyseal bone. A blunt-tipped nail would not penetrate the bone, and instead, might push the humeral head and increase opening of the fracture site. The leading end of each nail is slightly bent. Mild contouring is performed at a short distance from the tip so that the curve matches the inner contour of the metaphyseal flare. The nail diameter must follow the formula for upper extremities: nail diameter = 0.33 × diameter of the intramedullary canal. A 3.0 mm nail usually suffices even for teenagers.

12.2.6 Surgical Approach

In fractures of the proximal humerus (physeal injury or metaphyseal fracture), the incision is made proximal to the lateral epicondyle, and extends distally past the planned entry points to facilitate oblique insertion of the nails. It is recommended to create two distinct entry points (one for each nail), one above the other, as is done for supracondylar fractures (Fig. 12.5).

Following fascial incision and separation of muscle fibers, dissection is continued down to the bone. The entry holes in the distal portion of the lateral column are made with an awl, 10–20 mm above the lateral epicondyle (Fig. 12.6). During this step, the shoulder is internally rotated with the elbow in mid-flexion on the arm table to provide good support. However, the distal metaphysis must be firmly held to avoid misdirection of the awl, particularly toward the radial groove along which the radial nerve travels. The two nails are then

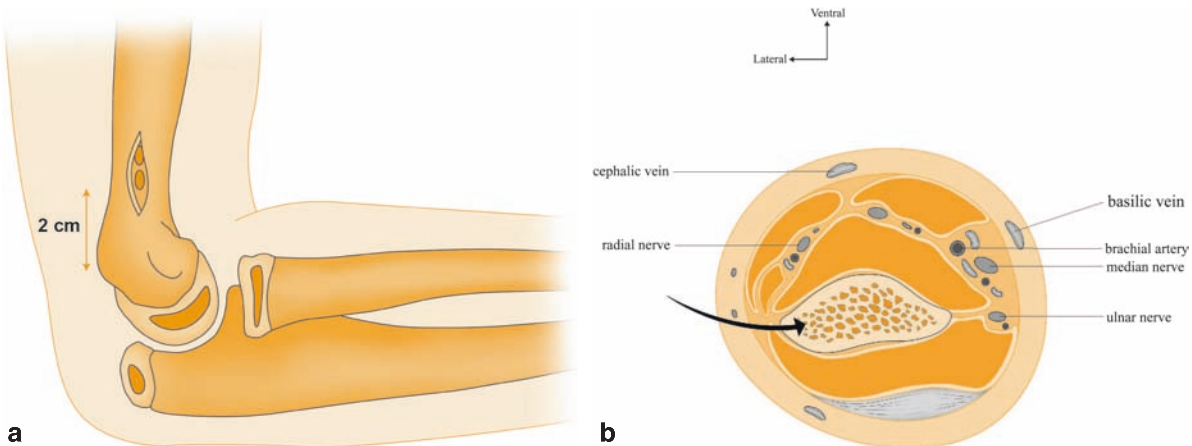


Fig. 12.5 Lateral supra-epicondylar incision, with the two entry holes made in the lateral supracondylar ridge 20 mm above the physis (**a**). Schematic cross-section illustrating the lateral approach (**b**)

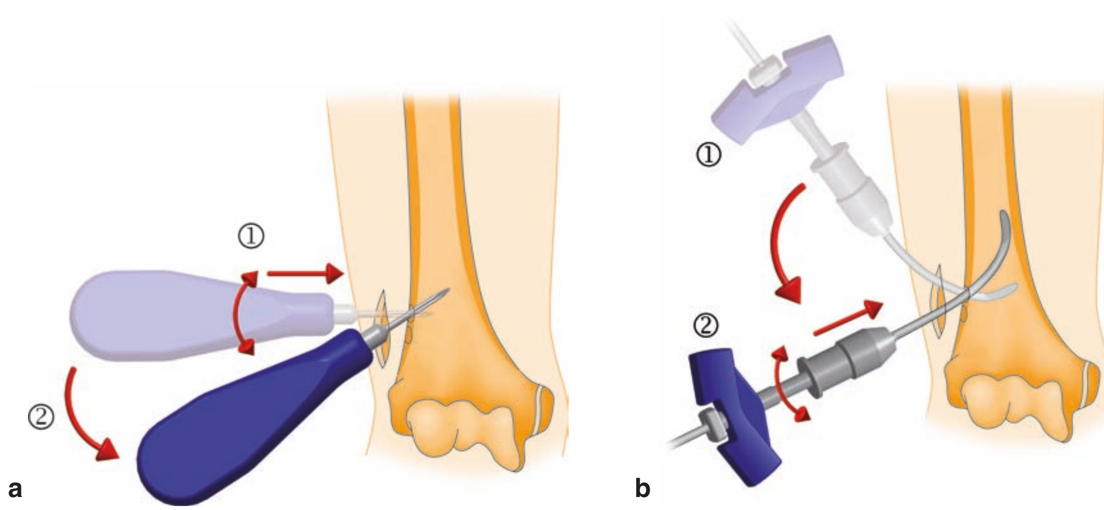


Fig. 12.6 The two lateral holes are created one above the other with a short awl (**a**). The first nail is inserted into the superior hole perpendicular to the bone and then advanced in an oblique upward direction (**b**)

successively inserted into the medullary canal using a T-handle. As their tapered tips tend to catch on the walls of the medullary canal, slight rotatory movements (clockwise and counterclockwise) are helpful to facilitate advancement.

12.2.7 Reduction and Crossing of the Fracture Site

Once the two nails have reached the fracture site, one of them is rotated 180° so that the nails point in opposite directions. Then, the assistant moves to the end of the arm table to hold the hand and wrist of the patient, and perform the reduction maneuvers. It may be necessary to apply a counter force to the child's armpit using, if needed, a drape wound up around the chest.

The preferred position for the arm and forearm is supination with the elbow extended. The shoulder is gradually brought into 110–120° of abduction and neutral or internal rotation, in order to reposition the metaphysis under the humeral head. One must keep in mind that the rotation center, a capsuloperiosteal flap, is located posteromedially. AP and lateral views allow to check the quality of reduction and, if satisfactory,

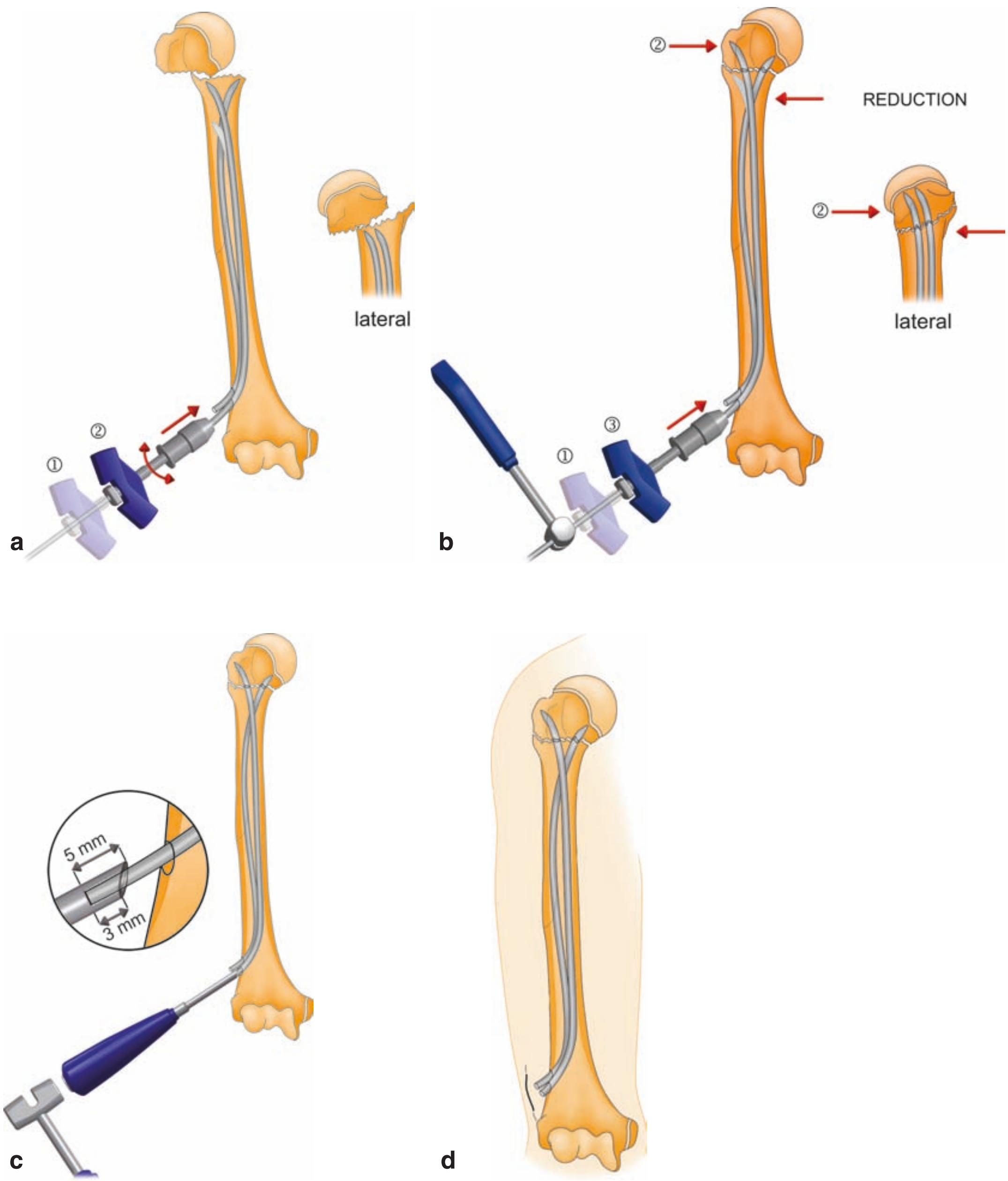


Fig. 12.7 Both nails are advanced up to the fracture site. Proximal tips look divergent on the AP view and parallel on the lateral view (**a**). After reduction, the nails are pushed into the metaphysis and sometimes into the epiphysis with the help of a slotted hammer (**b**). Distal nail ends are trimmed and impacted using the impactor so that only 3–5 mm of the nails will protrude from the humerus (**c**). Final construct after wound closure (**d**)

to visually control crossing of the fracture site, one nail at a time. The nails are systematically hammered into the proximal epiphysis (Fig. 12.7). In the few cases where reduction is incomplete, the nails can actually assist in reducing the fracture. In this case, both nails are directed toward the proximal fragment. Once the fragment is engaged, one of the nails is driven into the humeral head, and gentle rotation is performed using the T-handle combined with appropriate maneuvers to complete the reduction. The second nail is then pushed into the humeral head (Fig. 12.8).

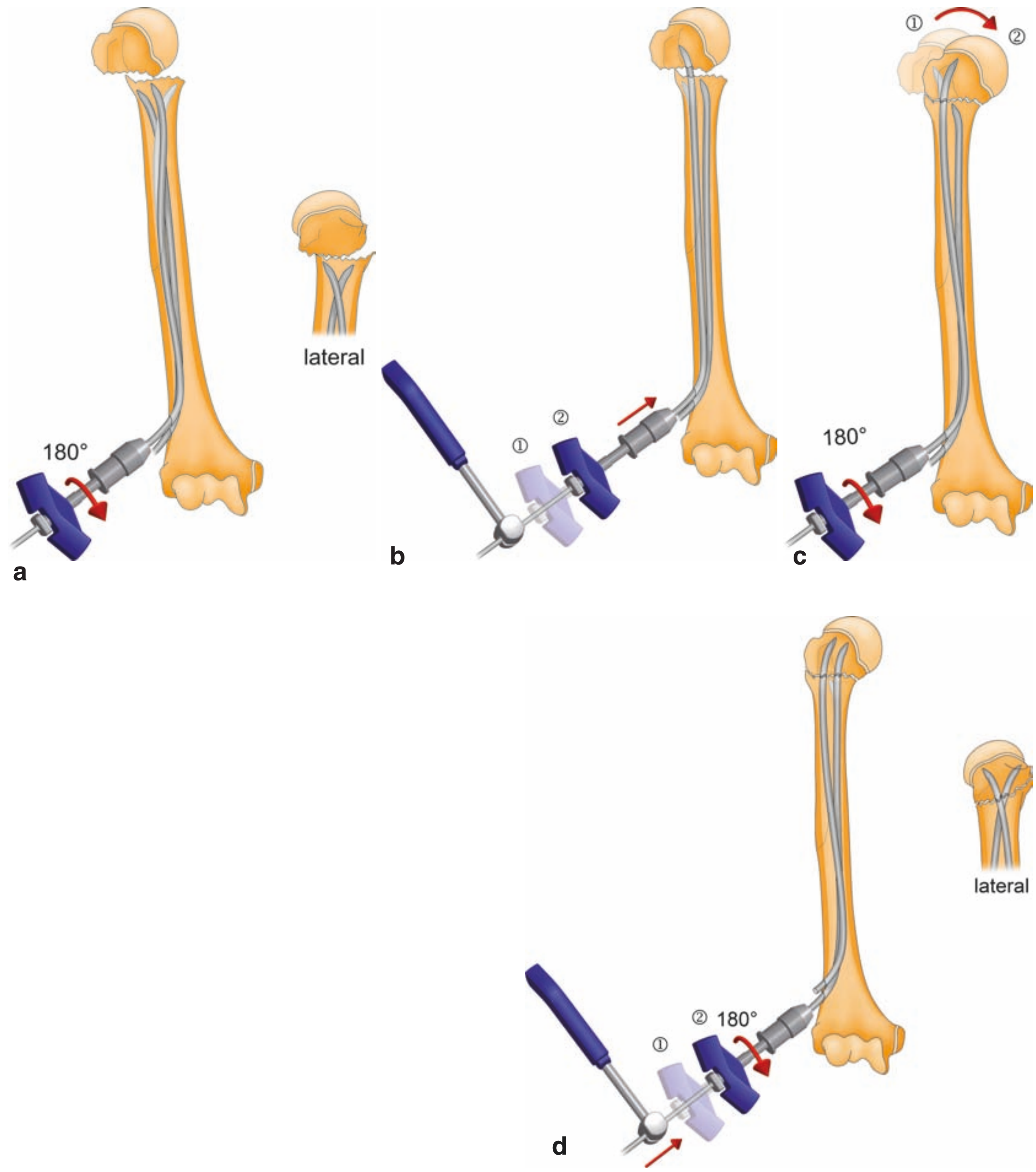


Fig. 12.8 If reduction is challenging as can be seen on the AP view, both nails are directed laterally and will look divergent on the lateral view (**a**). The first nail is pushed into the metaphysis with the help of a slotted hammer (**b**) and then rotated with its tip pointing medially to improve reduction (**c**). The second nail is then pushed into the humeral head (**d**)

12.2.8 Wound Closure

It is at the entry points into the lateral epicondyle that nail ends may be the most prominent. Therefore, careful trimming is important, as is the position of the entry points, which should be slightly proximal to the lateral epicondyle to allow burying of the trailing ends in the epicondylar muscles.

There are four useful tricks that help minimize the risk of skin irritation. One is to cut the nail to the desired length, slightly bend its distal end to facilitate later removal, push it with the help of a graft pusher so

Fig. 12.9 Titanium end caps were used over the distal ends of the nails to avoid injury to subcutaneous tissue

that it is just proud of the cortex, and proceed to final impaction. The problem with this method is that there is a risk of not correctly evaluating the length of the free end and cutting the nail too short. The second one is to leave the distal end straight, as the inherent elasticity of the material will keep the nail flush against the outer cortex of the lateral column. The third one is to use plastic or titanium protective end caps (Fig. 12.9). The fourth and the most effective method is to use an impactor with a 3–5 mm cannulated tip.

Then, the wound is thoroughly irrigated and closed in two layers without drainage.

12.2.9 Types of Fractures

12.2.9.1 Metaphyseal Fractures

The FIN technique for metaphyseal fractures is absolutely identical to that previously described for Salter II fractures. The only difference may lie in the difficulty to reduce fractures with overlapping fragments, which may require lateral decubitus positioning and application of a strong axial traction to the extremity.

12.2.9.2 Salter Types III and IV Physeal Injuries

In these rare types of intra-articular fractures, direct approach to the joint is necessary to reduce the articular fracture under visual control. The articular fracture can be fixed with a screw or a pin inserted transversally and carefully countersunk. The physeal injury can be managed by FIN, but this requires an additional approach, which could be avoided by using the existing intra-articular approach. However, the standard epicondylar approach offers one big advantage: it avoids an unnecessary arthrotomy for implant removal

12.2.9.3 Irreducible Fractures

Irreducibility is frequent in physeal injuries and very uncommon in metaphyseal fractures. It can be due to entrapment of the long head of the biceps tendon or periosteal flap. The latter does not require opening of the fracture site, whereas it is recommended to free the tendon of the long head of biceps. However, these are exceptional situations. As a rule, direct approach should be avoided as much as possible, more especially, as the deltopectoral approach often leaves hypertrophic, unsightly scars. In these specific cases, once reduction has been achieved, FIN is, indeed, the best choice since it provides excellent stability and eliminates the need for a second open approach to remove the nails (Fig. 12.10).

12.2.10 Postoperative Care

A dry dressing is applied to the supra-epicondylar entry site. For radiographic assessment, care should be taken to move the arm as little as possible.

Postoperative monitoring consists essentially in checking for the absence of axillary nerve palsy, which may occur secondarily to postoperative swelling. However, this complication is transient and resolves spontaneously within a few days.

The inherent stability of the construct generally makes complete immobilization unnecessary. The child should wear a simple sling during the first postoperative days, and particularly on first getting up. Then, the sling is worn continuously for 2–3 weeks.

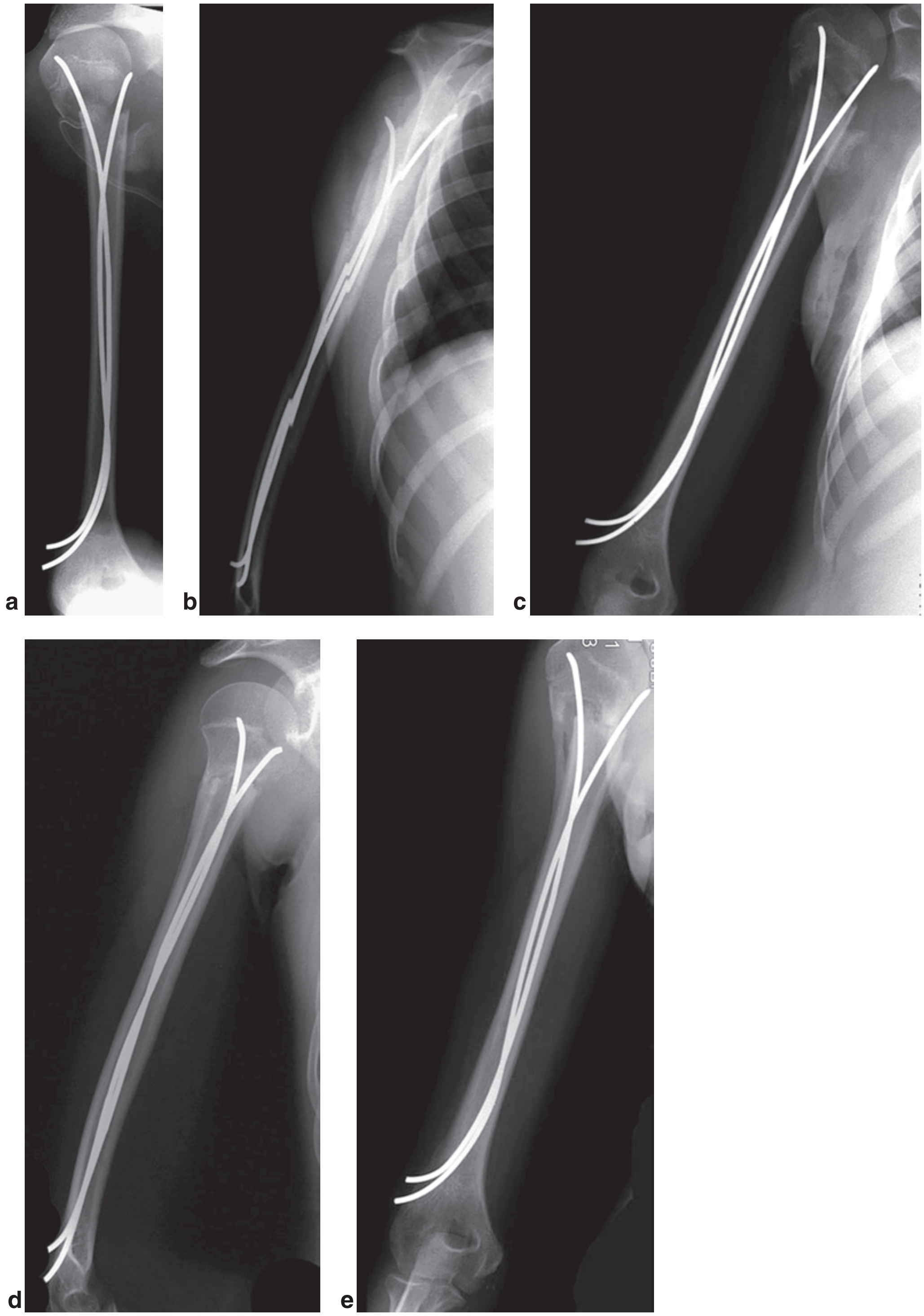


Fig. 12.10 A 14-year-old girl with an irreducible surgical neck fracture of the humerus and fragment overlap. An open approach was necessary to free the long head of the biceps tendon, and unipolar retrograde FIN was performed using two 2.5 mm nails. As seen on the radiograph, one of the nails has clearly "missed" the humeral head (**a**, **b**). Nevertheless, at 1 month, healing was progressing toward bone union with no secondary displacement (**c**). At 3-month follow-up, the fracture was united (**d**, **e**). Note: in spite of a precarious stabilization, bone union took place in 3 months. Again, let's emphasize the importance of AP and lateral checks

As soon as pain and swelling are controlled, that is, 2–3 days following surgey, the child is discharged from hospital.

12.2.11 Resumption of Activities

As soon as the child is back home, he/she can return to school but should continue wearing the sling. After 3 weeks, the child can gradually give up the sling and start self-rehabilitation by performing activities of daily living, as physeal injuries heal rapidly. Pendulum exercises are recommended for the shoulder. Any movement that places excessive load on the arm is strictly prohibited for about 6 weeks, which is the time for fracture to heal completely.

A radiographic assessment (AP and lateral views of the proximal humerus) is performed at 6 weeks. Return to high-impact sports is authorized only when bone union is achieved, that is, about 3–4 months after surgery, depending on the age of the child and the type of sport.

12.2.12 Implant Removal

Nails can be removed early as fractures of the proximal humerus heal rapidly. Because of the supra-epicondylar approach and the thin soft tissue coverage in this area, the distal ends of the nails are cut just short of the bone surface to minimize the risk of skin impingement. The problem is, as bone grows, the distal tips may become fully embedded in bone and just impossible to remove. This is the reason why it is advisable to remove the nails as soon as bone union is obtained, that is, from the second postoperative month. The removal procedure is performed on a day-patient basis using the initial lateral incision. The child is then cautioned against returning to sports within less than 1 month.

12.2.13 Postoperative Follow-Up

Depending on the age of the child, and in the absence of residual angulation (in which case bone remodeling would need to be closely monitored) or any complication that would necessitate special treatment, a radiographic assessment at 1 year is sufficient. The child is then considered as permanently healed.

12.3 Complications

12.3.1 Initial Complications

12.3.1.1 Neurologic Complications

According to Visser [8], initial neurologic complications are mainly observed after low-energy trauma, essentially induced by traction. The axillary nerve and the suprascapular nerve are mostly injured. One must keep in mind the numerous retrospective diagnoses of previously missed injuries, and the 50% rate of stretch injuries observed in minimally displaced or nondisplaced fractures in his series. This is why a thorough clinical examination at presentation is mandatory. Preoperative detection of these lesions is extremely important even if they generally have a good prognosis, since they resolve spontaneously and completely within a few weeks.

12.3.1.2 Vascular and Skin Complications

Vascular and skin complications are exceptional. They are only seen in severely displaced fractures or in case of direct trauma to the proximal humerus [3].

12.3.2 Specific Complications

12.3.2.1 Difficult Reduction and Instability

Irreducibility has been reported by many authors [2, 3], both in metaphyseal fractures and physeal injuries. It is due to entrapment of the long head of the biceps tendon or capsuloperiosteal flap. Guibert emphasized the importance of carefully checking for the absence of entrapment on a lateral view when reduction is incomplete. As previously said, it may have gone undetected during the initial diagnosis, but partial entrapment of the long head of the biceps tendon after healing will cause constant pain in the shoulder [9]. One must be even more cautious when there is 100% anterior displacement of the distal fragment. In cases of complete irreducibility, it is recommended to use an open approach (generally a deltopectoral approach) to address the problem and perform FIN.

Instability of the fracture site is more frequently associated with physeal injuries, and more particularly with Salter Type I fractures. The reason is the epiphysis is completely separated from the metaphysis, whereas in Type II fractures the medial wedge of metaphyseal bone that remains attached to the epiphysis is sufficient to ensure stability during reduction. Internal fixation is mandatory to stabilize the fracture and achieve an approximate equilibrium for impaction.

12.3.2.2 Implant-Related Problems

The lateral supra-epicondylar approach is inevitably associated with distal prominence of the nails. There are two reasons for this: the bone surface is very close to the skin, and there is little soft tissue coverage to protect the skin from the nail ends. Therefore, as previously said, special care should be used when placing the nails, and the nails should be removed as soon as bone union is obtained.

Another issue is the potential risk of misdirection when advancing the nails up the medullary canal, particularly the medial nail, which may jeopardize the axillary neurovascular bundle if incorrectly positioned. Therefore, it is essential to check for correct positioning under image intensification (AP and lateral views) prior to carrying on with the procedure. A common error is to restrict abduction of the upper limb prior to impacting the nails in the metaphysis, because abduction is needed for reduction and stabilization of the fracture site, particularly in physeal injuries. This may result in loss of reduction and increase the risk of misdirection (Fig. 12.10).

12.3.2.3 Joint Stiffness/Joint Pain

The surgeon must be able to detect, and above all, be able to correctly interpret this type of complication. Fractures of the proximal humerus do not lead, strictly speaking, to joint stiffness. Limitation of glenohumeral range of motion, which is often transitory, is most often due to a residual angulation. It gradually returns to normal as the deformity corrects itself during the remaining growth period. Therefore, rehabilitation is not necessary, let alone corrective osteotomy.

Pain, whether spontaneous or elicited by shoulder motion, is suggestive of a missed entrapment of the long head of the biceps tendon. Magnetic resonance imaging (MRI) is ideal to confirm diagnosis [9].

12.3.2.4 Avascular Necrosis of the Proximal Humeral Epiphysis

This extremely rare complication is encountered in Salter III or IV growth plate injuries. However, the transient devascularization resulting from separation of the epiphysis is followed by a gradual but complete revascularization, which does not seem to adversely affect the outcome [10].

12.3.2.5 Other Complications

Other complications such as sepsis or malunion are rare and have no specificity. They are managed as appropriate. No nonunions have been reported in the proximal humerus, so far.

12.4 Indications

Owing to the difficulty in immobilizing some metaphyseal or epiphyseal fractures in adolescents, there are quite a few indications for FIN in the proximal humerus (Case 1). As a matter of fact, reduction and stabilization are achieved with the shoulder in abduction. It is particularly tricky to apply a thoracobrachial orthosis with the arm in abduction or in the so-called "Statue of Liberty" position. Therefore, surgical stabilization should be preferred whenever reduction is considered.

In practice, owing to the high remodeling capacity of the proximal humerus, metaphyseal fractures are usually left unreduced. The child wears a simple bandage with elbow close to body [11]. In this respect, Beaty's reduction indications are most useful. It is safe to say that in adolescents aged 12–13 years or more, depending on the degree of skeletal maturity, gender, and amount of displacement, reduction and fixation of a metaphyseal or epiphyseal fracture are necessary (Case 2).

Similarly, multiply injured patients need stabilization of all their fracture sites to facilitate postoperative care and monitoring (Case 3). In these cases, FIN allows easy stabilization of fractures using minimally invasive approaches with minimal blood loss, and facilitates overall management of the child [7, 12, 13].

12.5 Contraindications and Limitations

The only contraindications to this technique are widely open fractures with severe skin and muscle damage, and children whose remaining growth potential will allow full realignment through bone remodeling.

Limitations to this technique are severe neurovascular injuries, which require a specific emergency treatment. In this case, it is wiser to use a strong fixation device, which will allow mobilization of the upper extremity, particularly if many dressings are to be applied under general anesthesia. The use of fixation screws or even an external fixator may be a good alternative, which however remains exceptional in adolescents [14].

12.6 Case Reports

12.6.1 Case 1

A 15 year-old girl hit by a car, presenting a Salter Type II fracture of the proximal humerus (a). Bipolar retrograde FIN was clearly challenging as shown by this "spaghetti-like" construct; the nails appear to intersect at four points (b, c). At 5-month follow-up, function was excellent (d) (Fig. 12.11).

Note: 2.5 mm stainless steel nails were used. Considering the size of the bone and the age of the child, 3.0 mm nails would have been more appropriate and easier to insert.

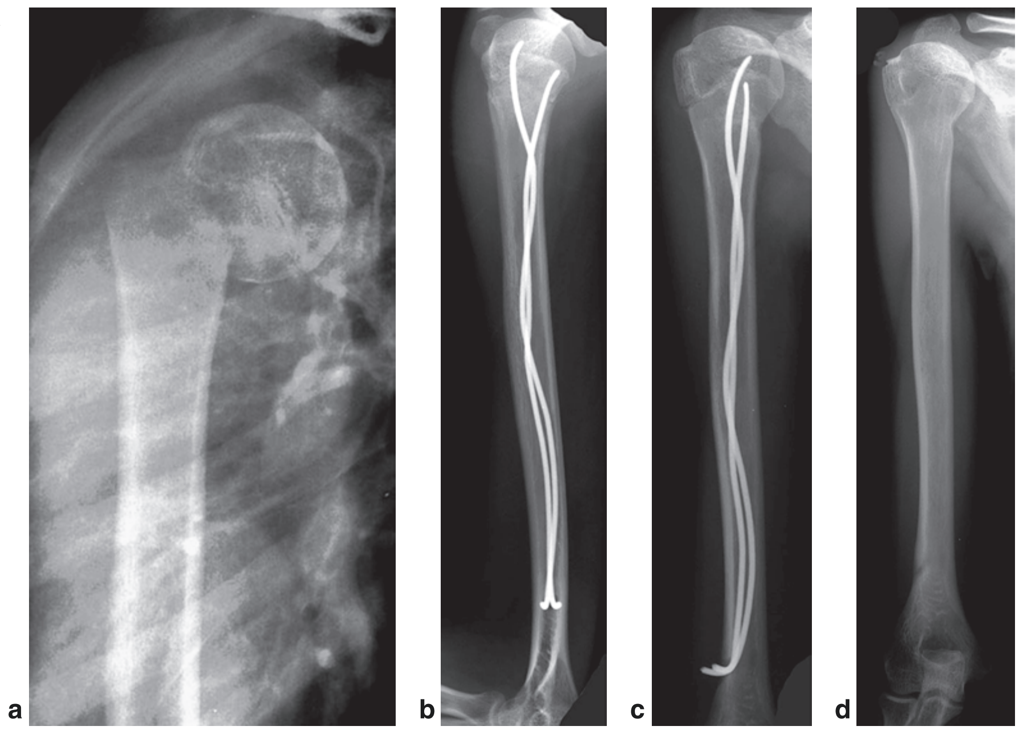


Fig. 12.11 Case 1

12.6.2 Case 2

After a fall from a horse, a 15-year-old girl presented with a metaphyseal fracture of the proximal humerus (a). Given the age of the child and the amount of displacement, unipolar retrograde FIN was performed using two 3.0 mm nails (b, c). Six months later, the child had regained excellent function of her shoulder and could resume horse riding, but 6 months later, she fell again and fractured her right clavicle (d) (Fig. 12.12).

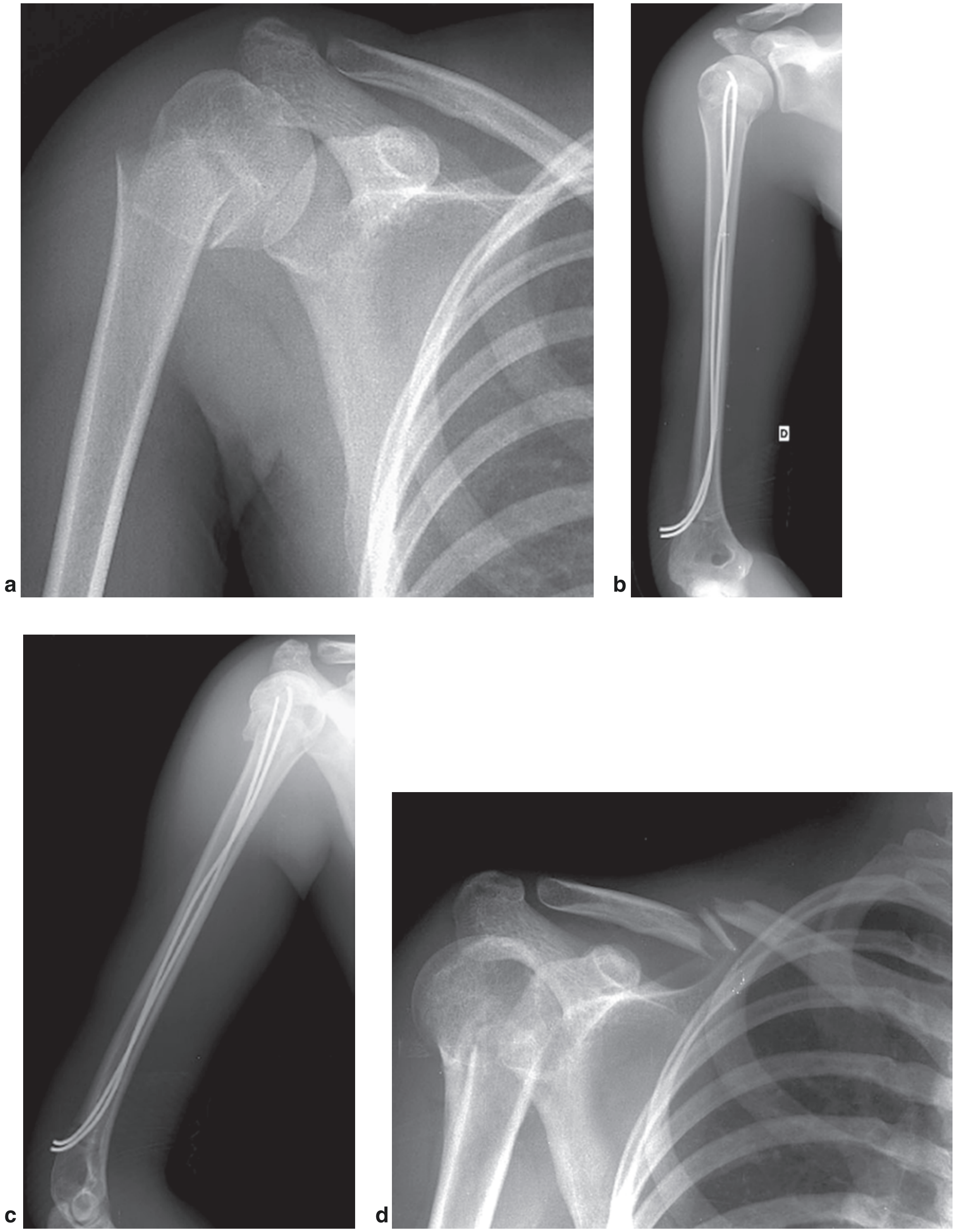


Fig. 12.12 Case 2

12.6.3 Case 3

A 2-year-old girl who sustained multiple injuries in a road traffic accident. She had a cervical spine injury (Fig. 12.13). She also had a severely displaced surgical neck fracture of the right humerus, (a) which was reduced under general anesthesia and treated with unipolar retrograde FIN using two 1.5 mm tapered nails (b, c). At 3-month follow-up, function was excellent and the fracture was united (d).

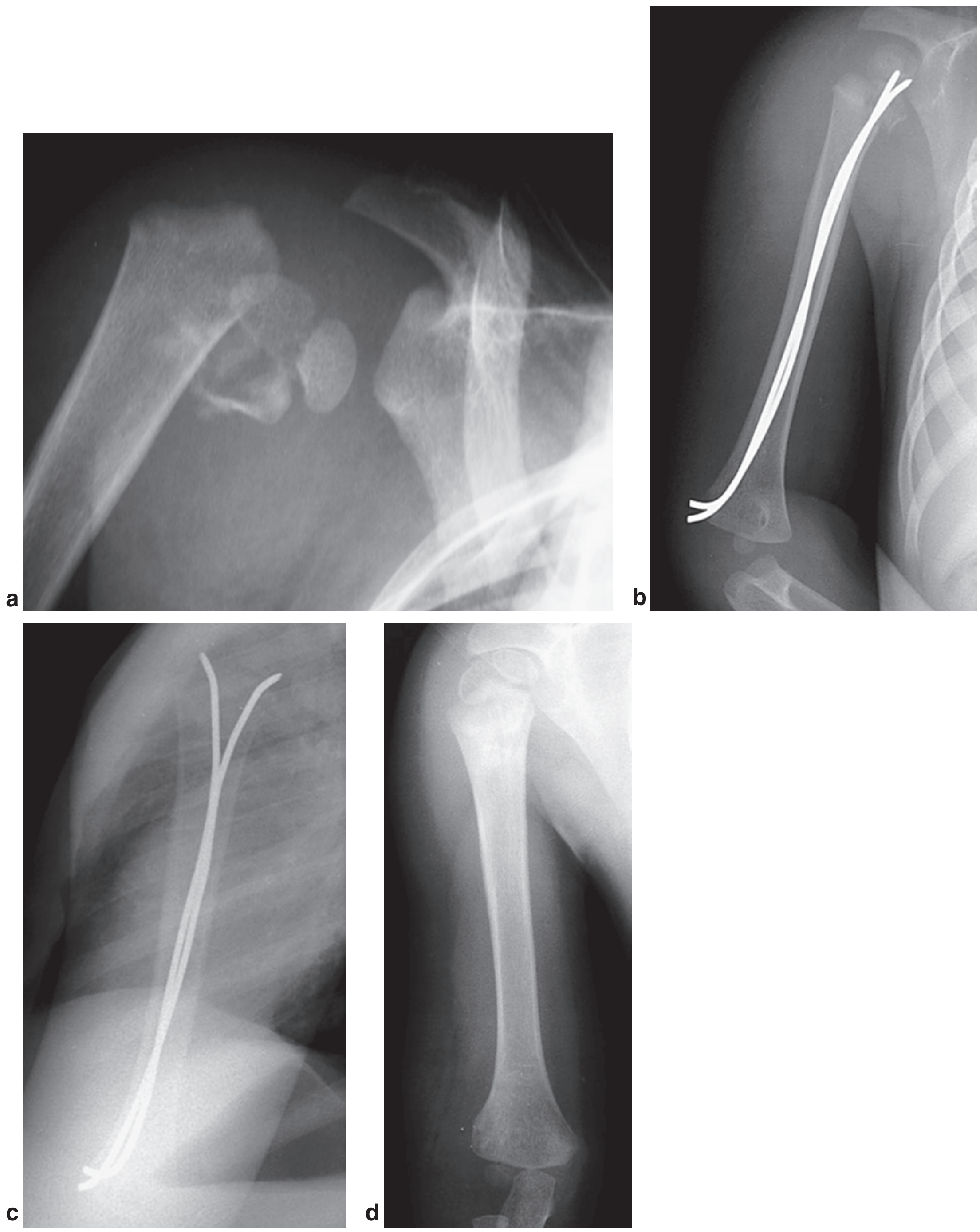
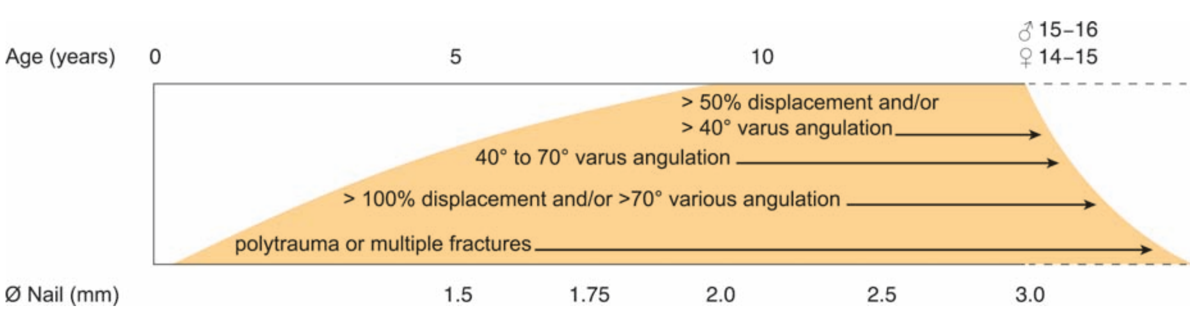


Fig. 12.13 Case 3

12.7 FIN and Fracture of the Proximal Humerus: Postoperative Management in the Absence of Complications

Day 0	• Postoperative AP and lateral radiographs • Vascular and neurologic monitoring • Operated hand is elevated • Pain killers + antiinflammatories
Day 1	• Protective sling; patient is allowed to get out of bed
Days 2–3	• Discharge with instructions • Early return to school • Gentle mobilization of shoulder and elbow, everyday
Three weeks postop.	• Sling removed • Self-rehabilitation
Six weeks to four months postop.	• Clinical and radiological follow-up • Implant removal is considered • Return to sports
One year postop.	• Clinical and radiological follow-up

12.8 FIN Indications: Fracture of the Proximal Humerus



12.9 Six Key Points

- Two 2.5–3.0 mm diameter tapered nails must be used in adolescents.
- Unipolar retrograde FIN is performed from a lateral supra-epicondylar approach.
- Nails should be pushed across the fracture site with the help of a slotted hammer.
- The surgeon must get the knack of rotating the nails to improve reduction.
- Careful trimming of nail ends and skin protection are critical.
- Patient's limb must not be immobilized.

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13 Humeral Shaft Fracture

Pierre Journeau

13.1 General

13.1.1 Epidemiology

Humeral shaft fractures are very infrequent in children (only 2–5% of all pediatric fractures) [1, 2]. Due to their etiology, they are predominantly seen in children aged less than 3 years or more than 12 years. As a matter of fact, most humeral shaft fractures, which occur in young children are the result of child abuse or birth trauma. In older children, they generally result from high-energy trauma and are sometimes associated with other injuries.

13.1.2 Mechanisms of Injury and Classifications

The simplest classification of humeral shaft fractures is based on location of the fracture site in the humeral diaphysis (proximal, middle, distal), alignment of fragments, and appearance of the fracture line. As to the mechanism of injury, it varies significantly according to age.

In the young child, fractures are often caused by twisting, particularly in abused children. Fractures from direct impact are rarer and have an oblique line, sometimes spiral shaped [3].

In contrast, adolescents will have transverse fractures due to direct impact, fall from a height, sport, or road traffic accident.

Birth trauma is a completely different story: it may occur when one arm presents with the head or during a difficult delivery. In this situation, it can be any type of fracture.

In older children, the clinical diagnosis is generally clear, based on the circumstances of the accident or the clinical picture: upper limb functional disability, severe pain, elbow supported with the other hand, and trunk bent to the affected side.

Radial nerve injury is the most commonly associated lesion due to the close proximity of this nerve, particularly in middle-third fractures. Before initiating a therapy, it is essential to rule out any other lesions and inform both the patient and his/her family of the examination results, although the presence of such lesions will not influence the therapeutic strategy.

13.2 Retrograde FIN Technique

The case we are presenting here is a displaced fracture of the middle third of the humeral diaphysis in an adolescent (Fig. 13.1) [4].

13.2.1 Anesthesia

General anesthesia is mandatory as regional anesthesia would require mobilization of the upper limb, which is almost impossible and could jeopardize neural structures, in particular, the radial nerve. A supraclavicular brachial plexus block can be performed, knowing that it will make postoperative neurological monitoring more difficult.

13.2.2 Patient Positioning

The child is positioned supine on the operating table, with the affected upper limb placed on a radiolucent

P. Lascombes, *Flexible Intramedullary Nailing in Children*,
DOI: 10.1007/978-3-642-03031-4_13,

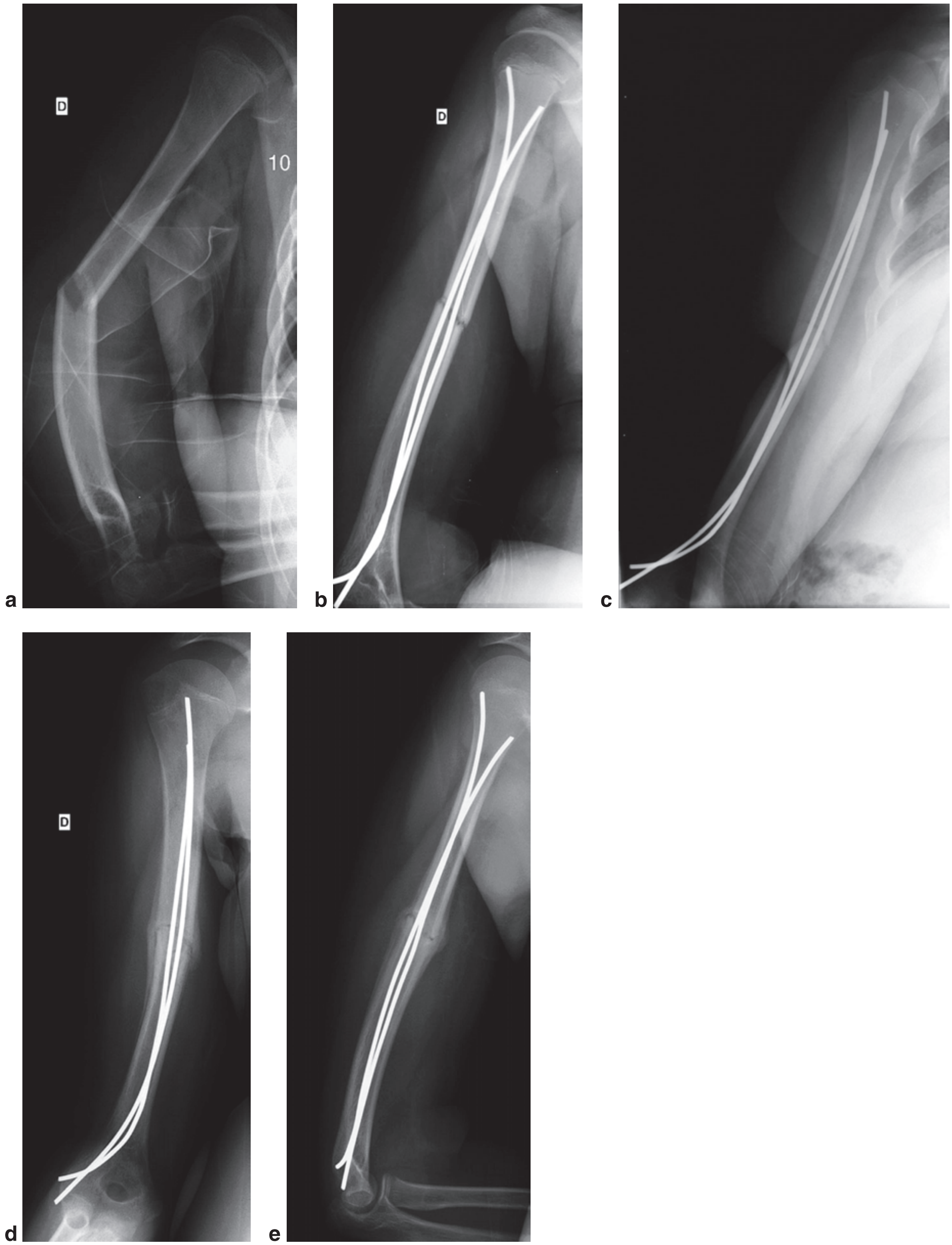


Fig. 13.1 A 12-year-old girl presented with a transverse fracture of the middle third of the humerus sustained in a fall on ice, with no neurovascular complications (**a**); unipolar retrograde flexible intramedullary nailing (FIN) using two 2.5 mm stainless steel nails (**b**, **c**); distinct external callus and evidence of union at 6 weeks (**d**, **e**)

arm table. The patient should be positioned as close as possible to the edge of the table to allow good visualization of the shoulder and proximal ends of the nails, next to the proximal metaphysis. It is not possible to use a tourniquet.

13.2.3 Image Intensifier

Image intensification is mandatory to control passage of the nails across the fracture site. The C-arm may be positioned right away to avoid further handling later on, but it will interfere with the assistant's workspace, or it may be positioned after draping has been completed. Whatever the option selected, the image intensifier should be positioned at the level of the axilla, parallel to the operating table and perpendicular to the arm table. The C-arm will need to be moved in a mediallateral plane to allow visualization of both the fracture site and the proximal humerus (Fig. 13.2).

Fig. 13.2 Patient is positioned on the table with the upper limb placed on an arm table, and C-arm properly positioned

13.2.4 Operative Field

The whole upper limb is sterile prepped up to the axilla and shoulder, as full mobilization of the arm and forearm will be required to perform reduction maneuvers and to access the fracture site (if necessary). A sterile upper extremity drape can be used that covers the arm table, the patient's trunk, and the lower limbs.

13.2.5 Selection and Preparation of the Implants

Either stainless steel or titanium nails can be used. The leading ends of some stainless steel nails need to be slightly rounded off and bent, whereas titanium nails are usually prebent. Follow the flexible intramedullary nailing (FIN) rule of thumb for nail diameter choice in upper extremities: Nail diameter = 33% of IM canal diameter. As the upper limbs are not weight-bearing, smaller diameter nails offer sufficient stability as well as easier crossing of the fracture site during insertion. The most commonly used diameters in adolescent humeral diaphyseal fractures range from 2.5 to 3.0 mm.

Then, both nails are gently contoured to achieve a curvature of 40° (approximately), the apex of which should be located at the fracture site at the end of the procedure.

13.2.6 Surgical Approach

In a middle-third fracture, the incision is made just proximal to the lateral epicondyle and extends distally past the points of entry for the nails to facilitate oblique insertion. It is recommended to create two distinct entry points, one above the other (Fig. 13.3). Following incision of the superficial fascia, the epicondylar muscles are separated longitudinally from one another by blunt dissection, which is continued down to bone. The entry holes in the distal portion of the lateral column are made with an awl, 20 mm above the lateral epicondyle. During this step, the upper limb is internally rotated with the elbow in mid-flexion to provide good support. However, the distal metaphysis must be firmly held to avoid misdirection of the awl toward the anterior aspect of the elbow and damage to the neurovascular structures. The two nails are then successively inserted into the medullary canal using a T-handle. To

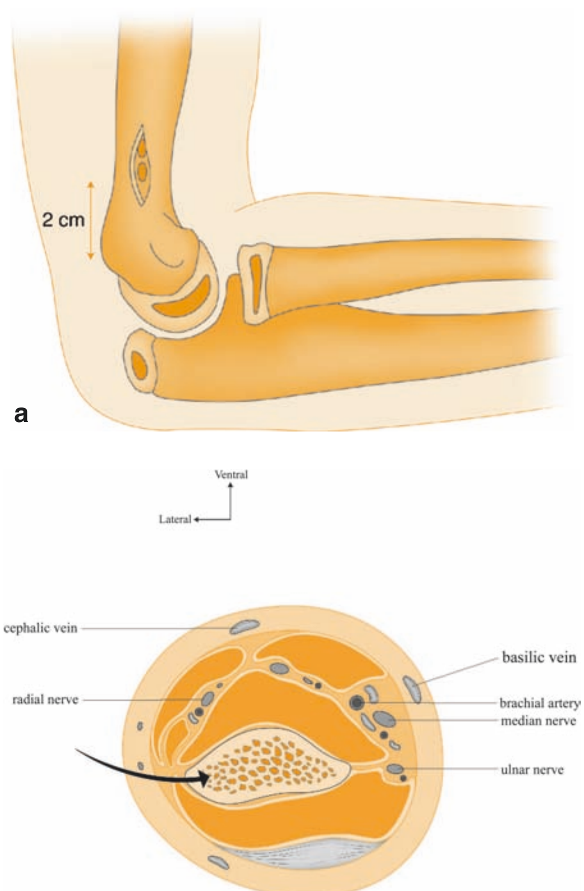


Fig. 13.3 Lateral supra-epicondylar incision: (**a**) both holes are made in the distal part of the lateral supracondylar ridge, approximately 20 mm from the physis; (**b**) schematic cross-section illustrating a lateral approach

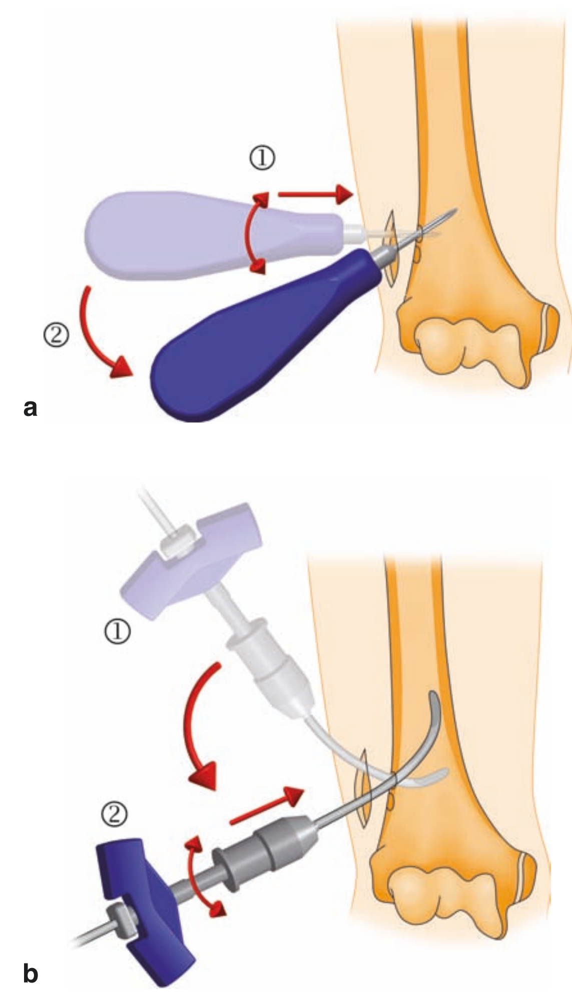


Fig. 13.4 The two holes are created one above the other with a short awl (**a**); the nail is initially positioned perpendicular to the hole and then advanced in an oblique upward direction (**b**)

facilitate advancement of the curved tip through the lateral column, the nail should be inserted in an upward rotational movement (with light hammer blows, if necessary) (Fig. 13.4).

13.2.7 Reduction and Crossing of the Fracture Site

Once the two nails have reached the fracture site, the assistant moves to the end of the arm table to hold the hand and wrist of the patient and apply axial traction, while a counter force is applied by a nurse to the child's armpit. If necessary, a drape may be wound up around the chest to act as a counter brace. The preferred position for the arm and forearm is supination with the elbow extended and the shoulder in 90° of abduction. Crossing of the fracture site (with the help of a slotted hammer) is performed under fluoroscopic guidance. Direction of the nails is dictated by the position of the proximal fragment; they should end up in the proximal canal, opposite to each other.

Particular attention should be paid to the direction of the nails in the lateral projection. Under no circumstances should the nails be directed toward posterior soft tissues in order to avoid damage to the radial nerve, which would result in postoperative radial nerve palsy (Fig. 13.5). Once the fracture site has been passed, the nails can be advanced up to the proximal humerus.

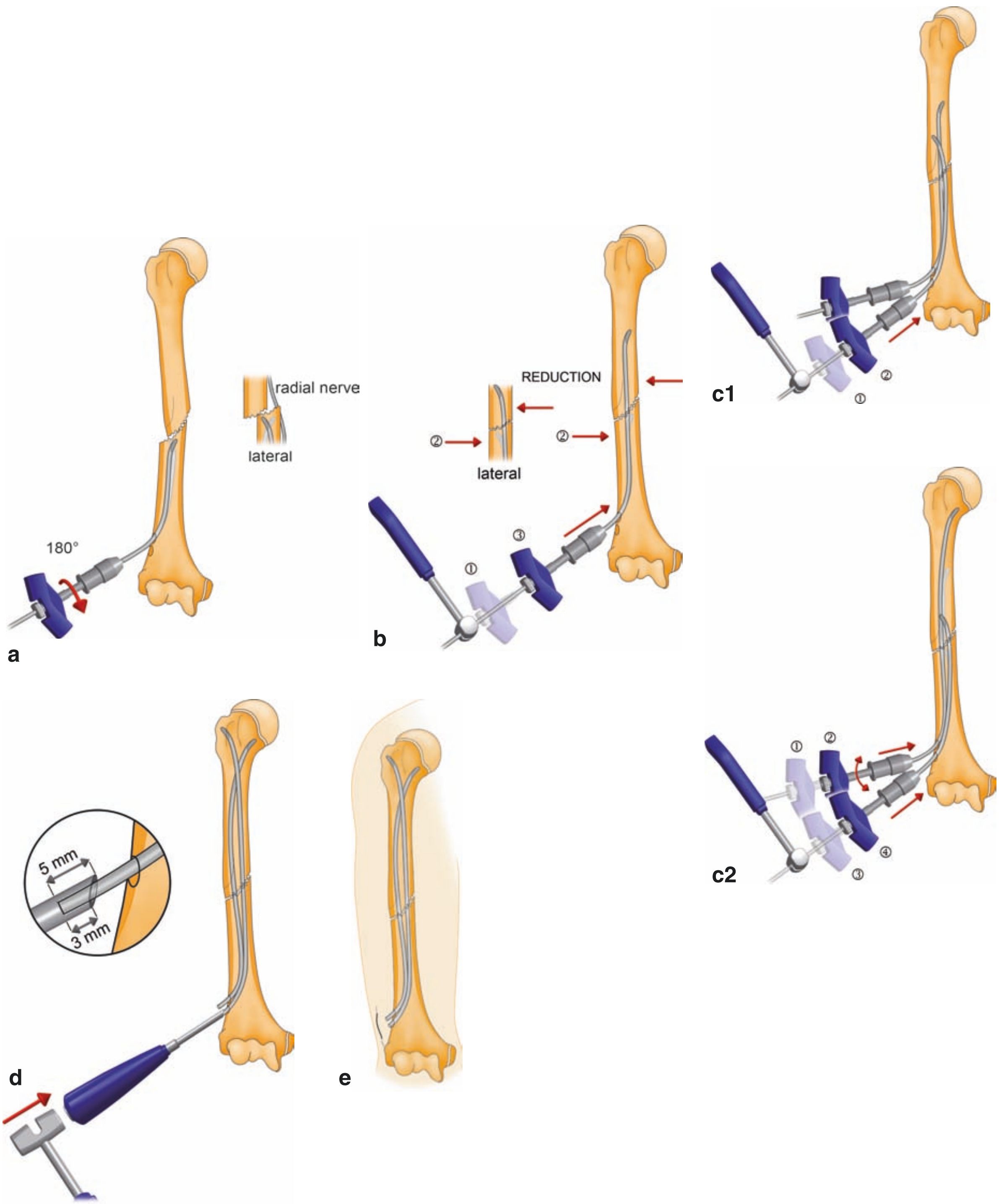


Fig. 13.5 The first nail is advanced up to the fracture site in the direction of the proximal fragment (in both AP and lateral planes). The nail must not be directed toward posterior soft tissues (**a**); (**b**) after reduction has been achieved, the nail is further advanced across the fracture site with the help of a slotted hammer; (**c1**) the second nail is inserted through the inferior lateral hole, advanced as far as the fracture site, and then across the fracture site with gentle tapping; (**c2**) it may be advisable to advance the first nail up to the neck of the humerus prior to driving the second nail across the fracture site; (**d**) once the two nails are properly positioned in the humeral neck, their distal ends are trimmed and impacted so that only 3–5 mm of the nails will protrude from the humerus; (**e**) final construct after wound closure

13.2.8 Final Reduction

When the nails are high enough in the medullary canal or cross the fracture site, the more proximal nail is rotated 180° so that it lies in the position of a medial nail. Thus, at the end of the procedure, both concavities will face each other with their apexes located at the fracture site. After reduction has been achieved, if the position of the nails is satisfactory, gentle hammer blows are used to complete seating. Actually, the curves themselves assist in reducing the fracture: the bending moment created by a curved nail within a long bone tends to angulate the fracture in the direction and plane of the concavity of the curve. It means that a valgus angulation in the fracture site can be corrected by using the concavity of the curve to produce a varus shift. At the end of the procedure, the surgeon must check that the proximal ends of the nails are firmly anchored in the cancellous bone of the metaphysis to avoid secondary migration.

13.2.9 Wound Closure

It is at the entry points into the lateral epicondyle that nail ends are the most prominent. For this reason, the nails should be inserted at least 20 mm proximal to the tip of the lateral epicondyle. Furthermore, the nail ends must be carefully trimmed and recessed.

There are four useful tricks that help minimize the risk of skin irritation. One is to cut the nail to the desired length, slightly bend its distal end to facilitate later removal, push it with the help of a graft pusher so that it is just proud of the cortex, and proceed to final impaction. The problem with this method is that there is a risk of not correctly evaluating the length of the free end and cutting the nail too short. The second one is to leave the distal end straight as the inherent elasticity of the material will keep the nail flush against the outer cortex of the lateral column. The third one is to use plastic or titanium protective end caps. The fourth and most effective method is to use an impactor with a 3–5 mm cannulated tip.

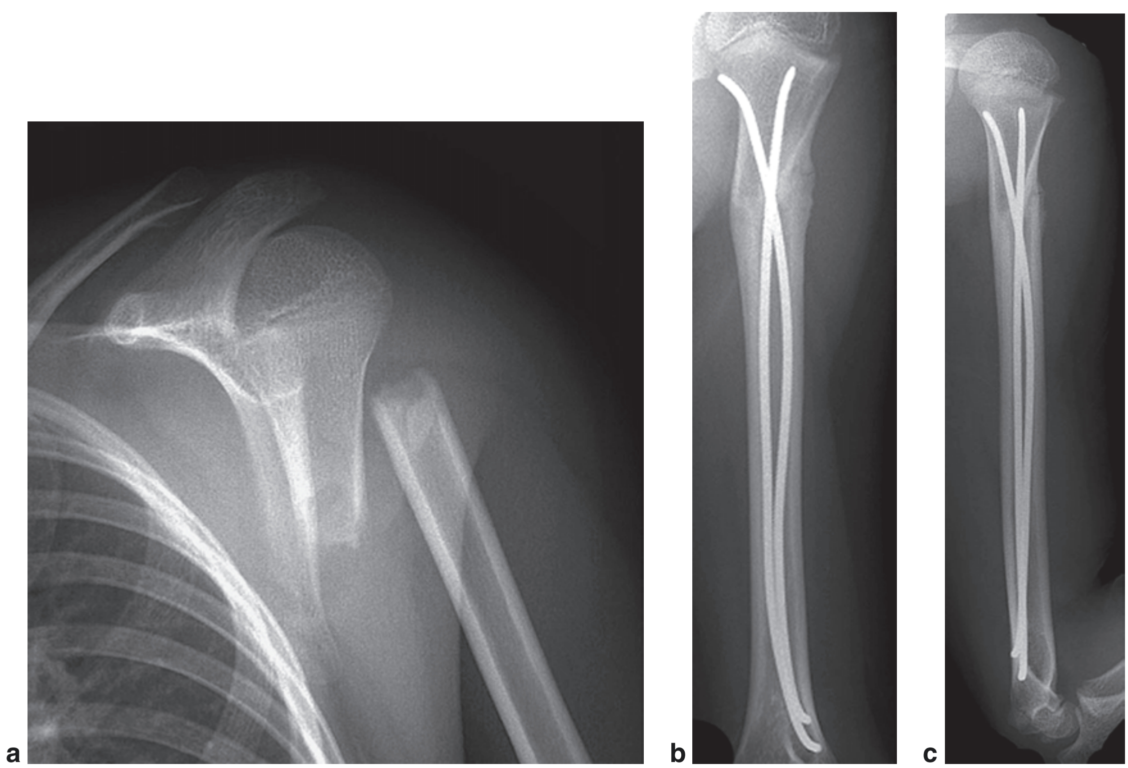


Fig. 13.6 A 12-year-old girl presented with a *left humeral fracture* at the middle-proximal third junction without associated complications (**a**). Due to the location of the fracture, their was a valgus displacement of the distal fragment and adduction of the proximal fragment that was pulled by the pectoralis major. FIN was performed from a lateral approach using two 3 mm titanium nails. Functional and radiological outcome was satisfactory (**b**, **c**)

Then, the wound is thoroughly irrigated and closed in two layers without drainage.

13.2.10 Types of Humeral Shaft Fractures

13.2.10.1 Proximal Third

These fractures are perfectly amenable to the retrograde FIN technique (as described above) (Fig. 13.6). However, care should be taken to perform maximum contouring just short of the bent tip. Should the apex of the arch not be located right at the level of the fracture site, it is advisable to use sharp nails, which will provide good purchase in the soft cancellous bone of the humeral head and will enhance stability of the construct. This technique is very similar to that used for fractures of the humeral neck.

13.2.10.2 Distal Third

It may not be possible to use the retrograde FIN technique in distal-third fractures, more especially as the fracture line is often oblique or spiral shaped. The problem is that the distance between the entry points on the lateral aspect of the distal humerus and the fracture site is too short to obtain an adequate arch (Fig. 13.7). In such situations, the first nail is inserted laterally and the second nail medially [5]. An entry

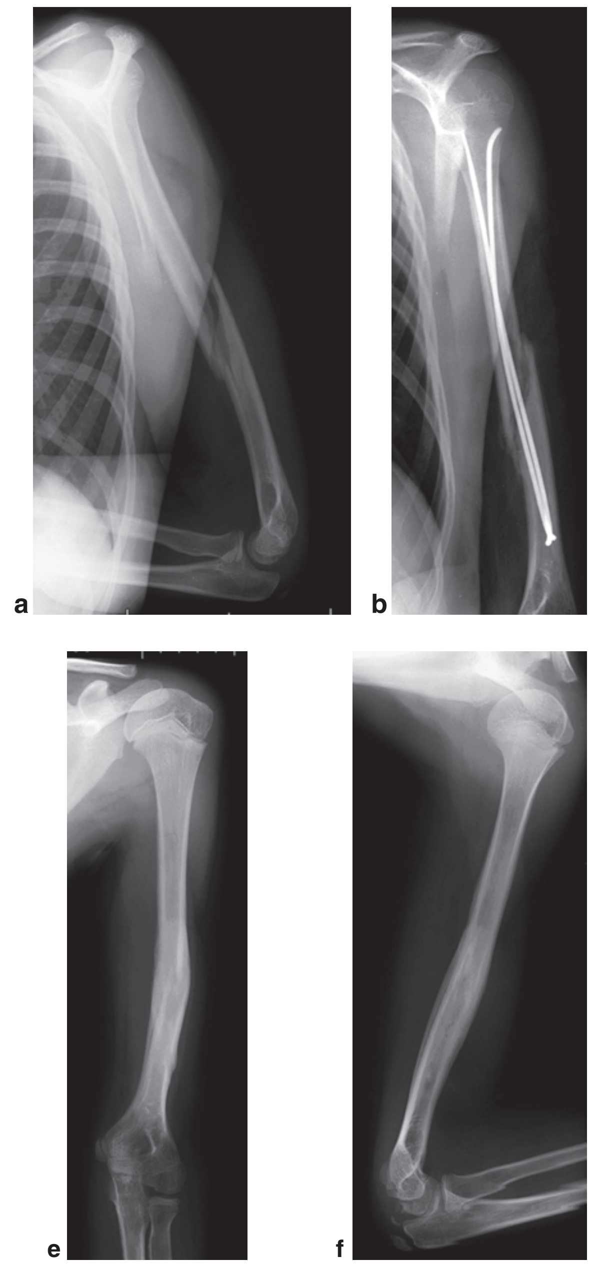


Fig. 13.7 A 13-year-old boy presented with a spiral fracture in the middle-distal third of the humerus caused by violent twisting during a brawl (**a**); unipolar retrograde FIN was performed using two 2.5 mm titanium nails, which provided good sagittal alignment (**b**). AP view shows inadequate reduction (**c**). Note that entry points were positioned too high; however, 2 months later, union was achieved (**d**); 4 months later, the radiological result was satisfactory (**e**, **f**)

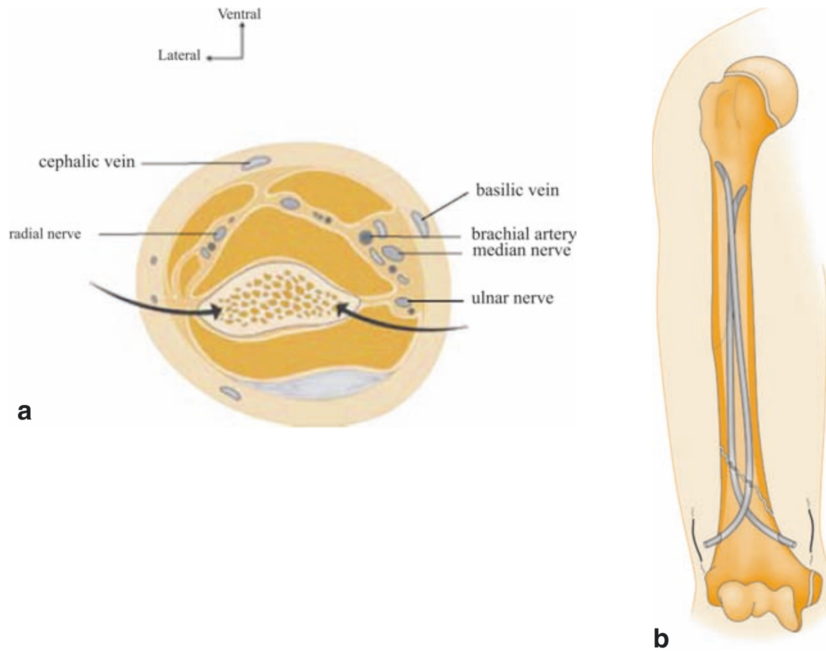


Fig. 13.8 Bipolar retrograde FIN technique using one lateral nail and one medial nail. Indicated in certain distal humerus fractures. (**a**) Crosssection illustrating the surgical approaches available; (**b**) final construct

point is created in the medial column (Fig. 13.8) just proximal to the medial epicondyle so that the two holes are aligned. When inserting the medial nail, it is recommended to pass behind the ulnar nerve to avoid interference with the neurovascular pedicle, on the medial aspect of the elbow. The nails are then advanced across the fracture site as previously described. To ensure that the curve will be in a distalmost position, both nails must be sequentially bent as they are advanced up the medullary canal (Case 1). In this way, a strong, symmetrical anchorage can be obtained both proximally and distally, with adequate bending.

Alternatively, unipolar antegrade FIN may be considered as in supracondylar fractures (see Chap. 14).

13.2.11 Postoperative Care

A dry dressing is applied to the wound surface. AP and lateral X-rays are taken without moving the arm.

Postoperative monitoring consists essentially in checking for the absence of radial nerve palsy, which may occur secondarily to postoperative swelling. In this case, it is transient and resolves spontaneously within a few days.

Good stability of the construct generally makes complete immobilization unnecessary. A simple sling is worn for a few days, beginning the day of surgery. During the immediate postoperative period, it is worn permanently to relieve pain, and then occasionally for 2–3 weeks.

When pain and swelling are controlled, that is, 2–3 days after surgery, the child is discharged from hospital.

13.2.12 Resumption of Activities

As soon as the child is back home, he/she can return to school but should continue wearing the sling. However, very rapidly, the child is encouraged to gently mobilize his/her elbow and shoulder for a few minutes, everyday. After 2–3 weeks, the child can do without the sling, and starts self-rehabilitation by performing activities of daily living and pendulum exercises for the shoulder. Any movement that places excessive load on the arm is strictly prohibited as long as healing is not complete.

A radiographic assessment is performed at 6 weeks. Return to sports is authorized only when bone union is achieved, that is, between 3 and 6 months after surgery, depending on the child's age and the type of sport.

13.2.13 Implant Removal

Prolonged implantation of the nails is not recommended as they will be all the more difficult to remove. When the humerus is approached laterally, there is little soft tissue coverage over the bone. For this reason, the distal ends of the nails are cut just short of the bone surface to prevent skin impingement. The problem is, as bone grows, the distal tips may become fully embedded in the epicondylar bone and can no longer be extracted. This is the reason why it is advisable to remove the nails as soon as bone union is obtained, between the fourth and the sixth postoperative month. The removal procedure is performed on a day-patient basis using the initial lateral incision. The child is then cautioned against returning to sports too early (within less than 1 month).

13.2.14 Postoperative Follow-Up

Depending on the age of the child, and in the absence of residual angulation (in which case bone remodeling would need to be closely monitored) or any complication that would necessitate special treatment, a radiographic assessment is routinely performed 1 year after removal of the device. If everything is fine, the child can be considered as permanently healed.

13.3 Complications

13.3.1 Initial Complications

13.3.1.1 Neurologic Complications

Neurologic complications [6] are the most frequent complications of middle-third fractures – although their rate is not accurately known. The radial nerve is involved in most cases due to its anatomic location. The result may be complete motor deficit, sensorimotor deficiency, or incomplete motor deficit with mild sensory dysfunction.

Both the child and his/her family must be informed of this preoperative status, and it should be recorded in the patient's chart. However, fracture-associated radial nerve palsy has no influence on the therapeutic strategy and is not a contraindication to FIN.

It may also occur after surgery. In this case, it is important to know whether it is complete or partial. The most frequent causes of postoperative radial nerve palsy are swelling and reduction maneuvers. Other causes include: misdirected nail, bone chip, radial nerve entrapped in the fracture site.

Although paresis has a good prognosis and usually regresses within a few days, complete radial nerve palsy must be monitored and evaluated at regular intervals. A specific rehabilitation program is necessary (see Chap. 10). If no signs of recovery are present at 3 weeks, electromyography is recommended. If signs are observed, monitoring and rehabilitation can be continued. Otherwise, surgical exploration of the radial nerve trunk should be performed [7].

Other nerve trunks are seldom involved.

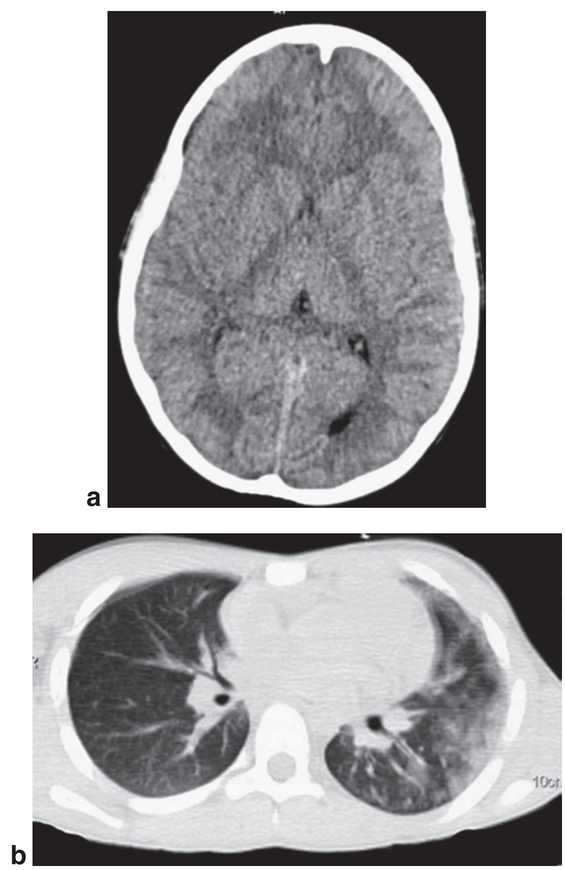


Fig. 13.9 A 12-year-old girl presented with multiple injuries sustained in a car accident that occurred at 7.00 am. Subdural hemorrhage along the falx cerebri (**a**), *left pulmonary contusion* (**b**)

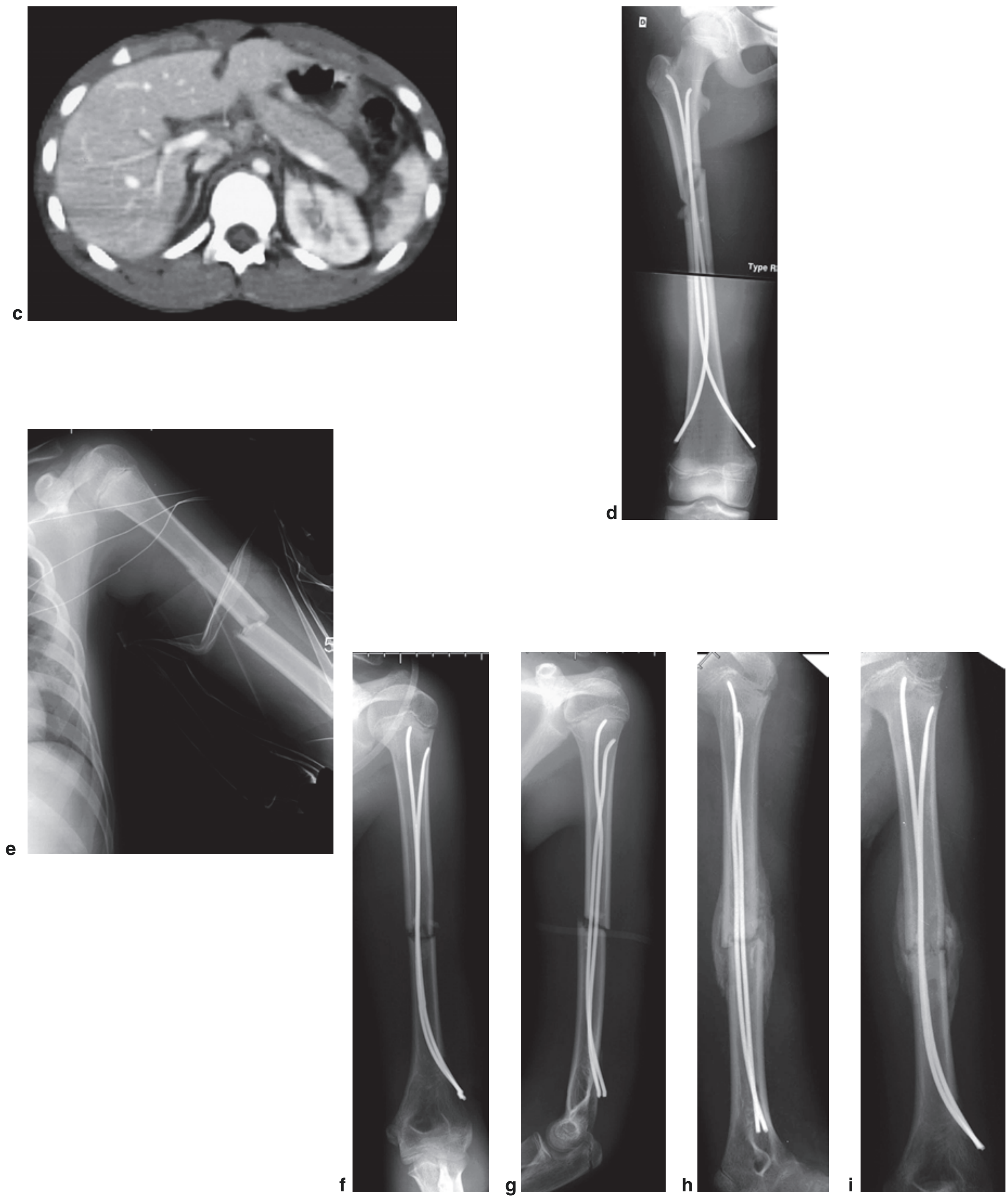


Fig. 13.9 (*cont.*) Hematoma of the inferior pole of the spleen (**c**), femoral fracture which will be treated by FIN (**d**) Cauchoix type II open fracture of the *left humerus* (**e**). Five hours later, two 2.5 mm titanium nails were inserted using an open FIN technique (**f**, **g**). Six weeks later, the healing process was going well (**h**, **i**)

13.3.1.2 Vascular and Skin Complications

Vascular and skin complications are exceptional. They are only seen in severely displaced fractures (Fig. 13.9).

13.3.2 Specific Complications

13.3.2.1 Difficult Reduction and Instability

In narrow medullary canals, particularly in young children, reduction may be difficult to achieve and insertion of the nails just impossible. Reduction may also be challenging in three-part fractures or in case of muscle entrapment. These exceptional situations require an open lateral approach to the fracture site.

Many fractures involving the distal third of the humerus are spiral shaped, which makes it difficult to achieve stabilization, using only a lateral approach. In this case, it is advisable to use a bipolar retrograde or unipolar lateral antegrade insertion technique.

13.3.2.2 Implant-related Problems

Implant-related problems are specific to the lateral epicondylar approach. As a matter of fact, in this area, the bone is right under the skin, with no soft tissue between the nail ends and the skin. For this reason, the entry points should be positioned 10–20 mm proximal to the lateral epicondyle. In addition, the distal ends of the nails should be cut just short of the bone surface, and the implants should be removed as soon as bone union is obtained.

13.3.2.3 Joint Stiffness

No elbow or shoulder stiffness has been reported, whatever the location of the fracture in the humeral shaft. But, skin irritation at the lateral or medial entry site may temporarily cause restriction of the elbow movement.

13.3.2.4 Delayed Union and Nonunion

As the upper extremity is nonweight bearing, it is not uncommon to have longer healing times than in other pediatric traumatic injuries. In practice, a long healing time means later return to sports activities. However, no nonunions have been reported so far.

13.3.2.5 Other Complications

Other complications may occur such as malunion (Case 1) or sepsis (Case 2), but they are very rare, have no specificity, and can be managed in the usual manner.

13.4 Indications

Indications for FIN in older children are justified considering the difficulty in immobilizing a humeral shaft fracture in these young patients. One considers that children aged 11–12 years or more with a middle-third fracture are amenable to internal fixation. Indications regarding distal-third fractures are even wider as this type of fracture is often unstable and difficult to manage by orthopedic means. In contrast, proximal fractures have a high potential to remodel owing to their close proximity to the proximal humeral physis, and they are also much easier to stabilize by closed means. Therefore, indications for internal fixation are rare [3, 8–12].

Gustilo type I and II open fractures are good indications for FIN as monitoring and postoperative management are facilitated.

Children with multiple injuries or fractures (Fig. 13.9) need stabilization of all their fractures to facilitate postoperative care and monitoring. FIN provides a straightforward way of dealing with these difficult cases: mini- incision approach, minimal blood loss, easier overall management of the child [13].

13.5 Contraindications and Limitations

The only contraindications to this technique are widely open fractures with severe skin and muscle damage. A major limitation to this technique is the presence of severe neurovascular lesions, which require a specific emergency treatment. In such a situation, it is wiser to use a strong fixation device, which will allow mobilization of the upper extremity. An external fixator may be a good option.

13.6 Case Reports

13.6.1 Case 1

After a fall from a horse, a 15-year-old girl presented with a short spiral fracture at the distal end of the humerus (a). As the fracture site was very unstable, a bipolar retrograde FIN with two 2.5 mm stainless steel nails was performed using a combined lateral and medial approach, which provided adequate reduction and good stability (b, c). However, impaction at the fracture site caused gradual migration of the nails, which eventually protruded through the skin (d, e). As union had not yet taken place, both nails were removed 1 month after implantation (f). A light bandage was immediately applied with elbow close to the body, and union was achieved within the following weeks. At 5 months, the young girl had regained full function of her elbow and shoulder and could return to sports in spite of a valgus malunion (g) (Fig. 13.10).

Note: The nails were too thin. Considering the age of the patient and the size of the humeral shaft, 3 mm diameter nails would have been more appropriate. Moreover, they crossed each other at the fracture site, which resulted in instability. The area of greatest convexity should have been located further distally.

Fig. 13.10 Case 1

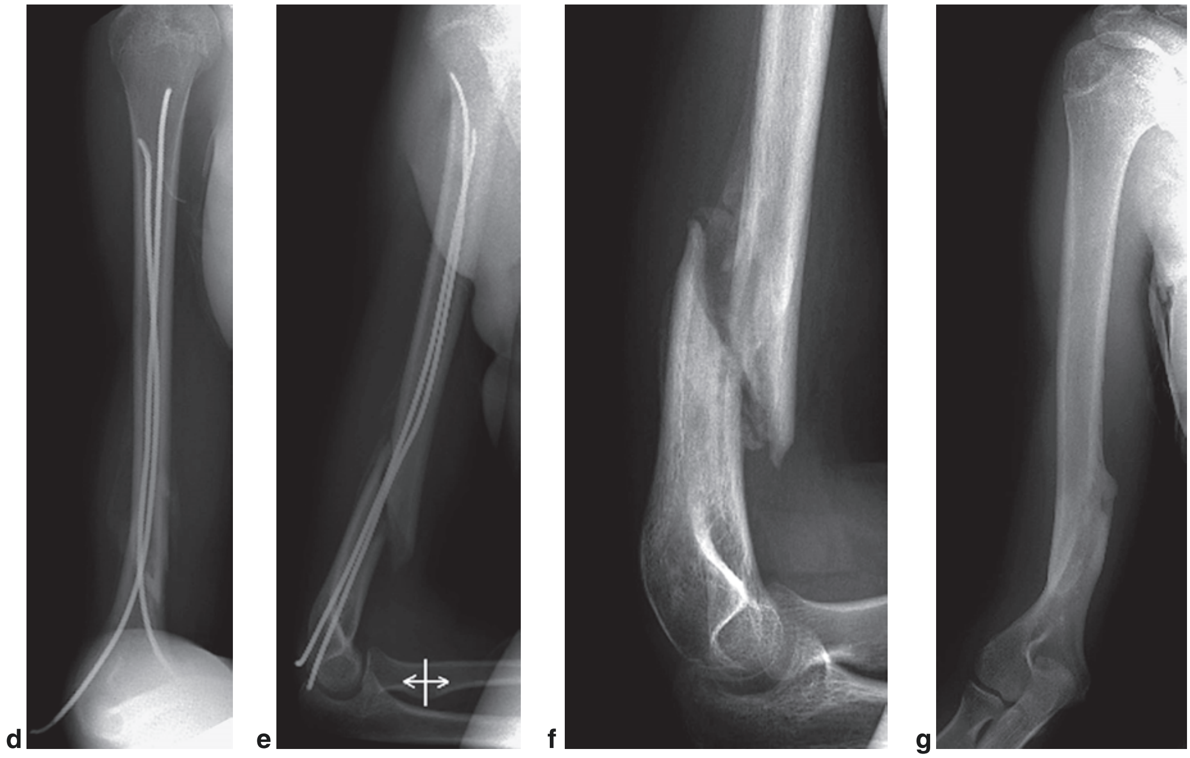


Fig. 13.10 (*cont.*) Case 1

13.6.2 Case 2

A 13-year-old girl sustained a transverse fracture of the middle third of the right humeral diaphysis (a). An emergency FIN procedure was performed using two 2.5 mm stainless steel nails. There were no associated skin or neurovascular lesions (b, c). Skin irritation at the entry sites was noted postoperatively. One month after implantation, the ends of the nails protruded through the skin at the lateral epicondyle, causing a hypertrophic response. The X-ray shows a normal healing process (d). In view of the local skin complication, it was decided to remove the implants (e). As a precautionary measure, a Mayo Clinic bandage was applied and healing progressed uneventfully until the fourth month. Then, a bone defect was observed at the fracture site without any clinical or biological symptoms (f). No complaint from the child for 1 full year, and then 18 months after the procedure, she was admitted again to hospital for a fistula opening on the lateral aspect of her arm at the level of the fracture site. Imaging confirmed both the bone sequestra and the fistula (g–i). She had to be reoperated on for excision of fistula tract and curettage of osteitis. She was treated with 3 months of antibiotic therapy, first intravenously and then per os. Bacteriological tests revealed the presence of staphylococcus aureus. Treatment was efficient, and after 3 months gradual filling of the defect was observed (j). At 6 months, functional outcome was excellent and bone union was achieved (k) (Fig. 13.11).

Note: the potential risk of osteomyelitis after surgical treatment of a fracture does exist, although the rate is very low; two cases in one thousand in our series).

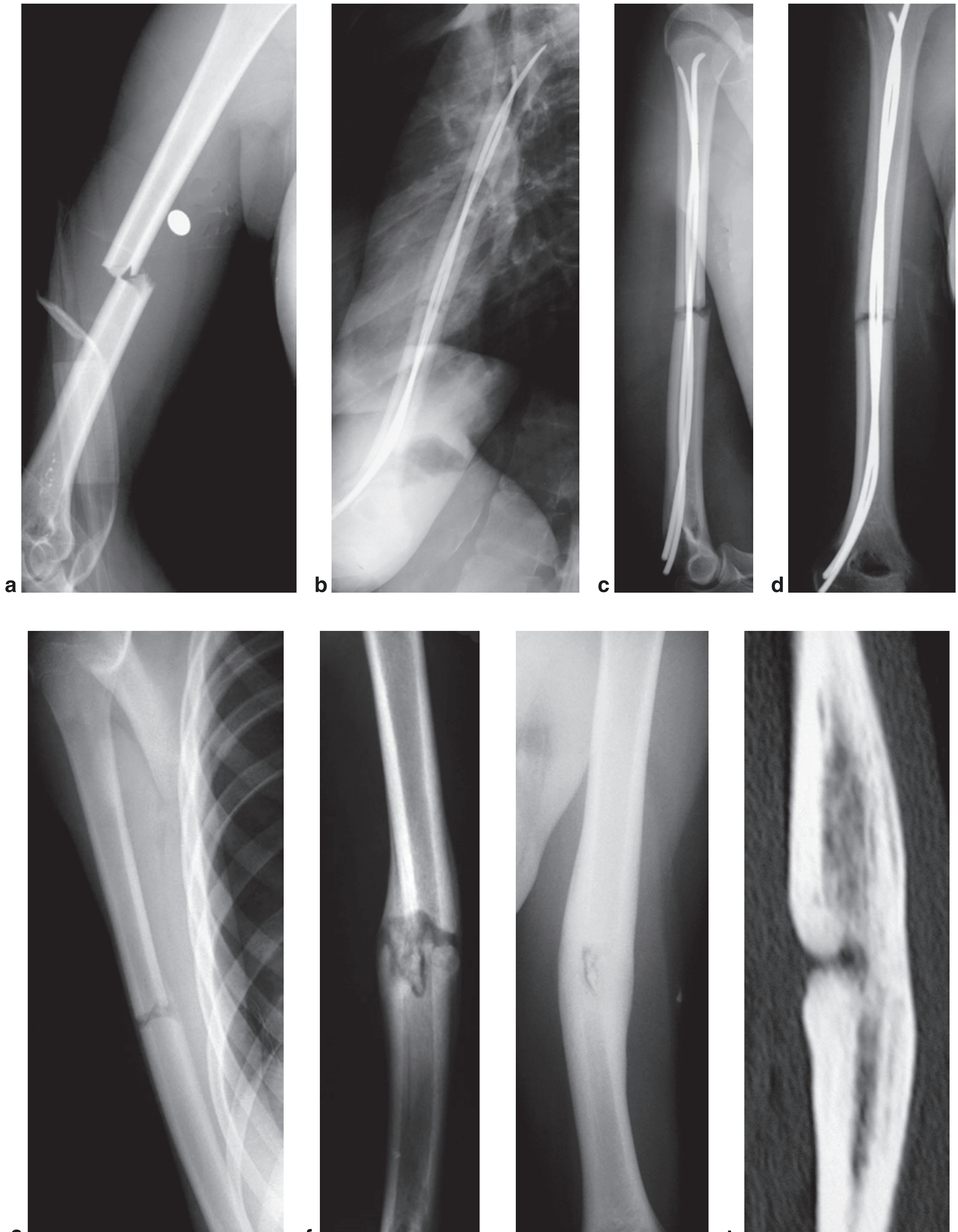


Fig. 13.11 Case 2

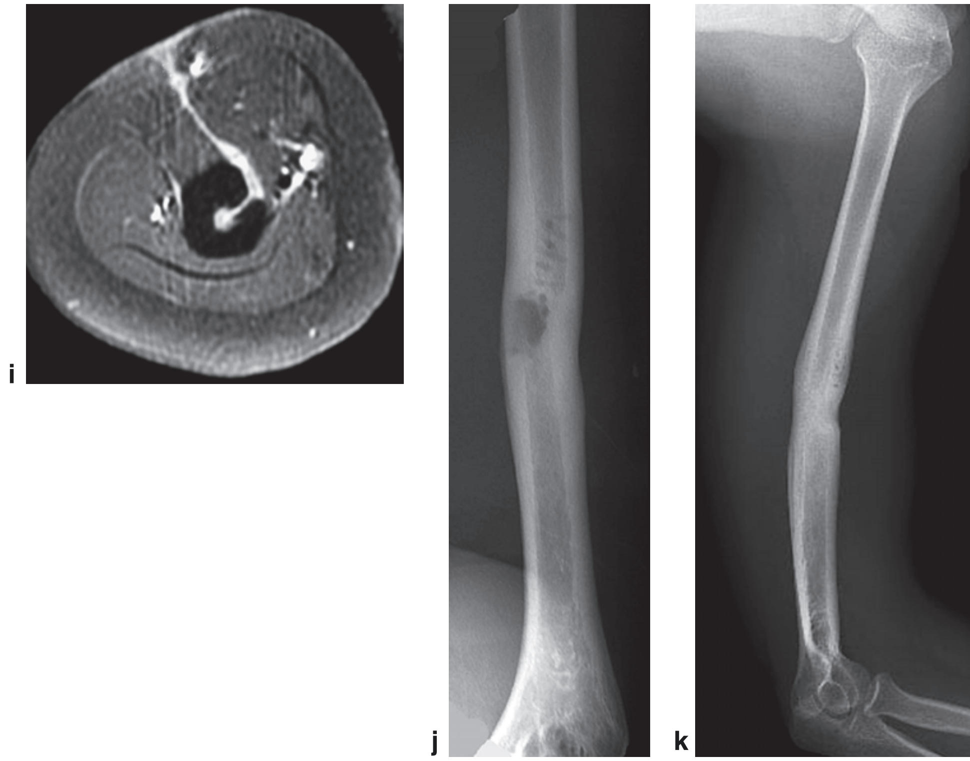


Fig. 13.11 (*cont.*)
Case 2

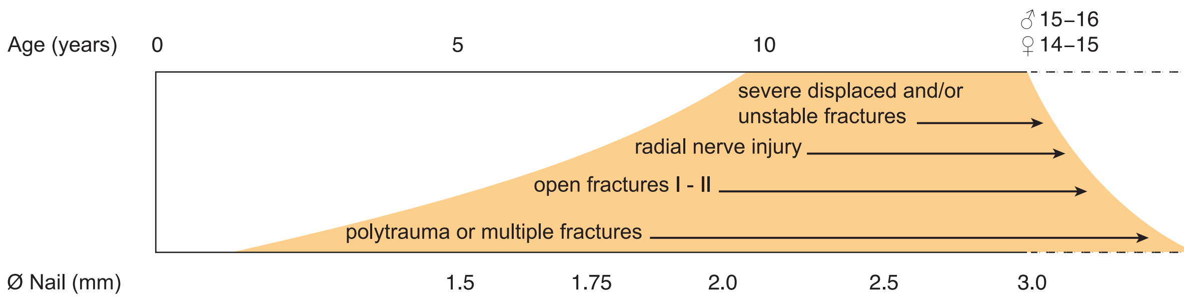
13.7 Six Key Points

- Two 2.5–3 mm diameter nails with curved tips should be used in adolescents.
- FIN is generally performed using a unipolar retrograde technique and a lateral supra-epicondylar approach.
- When crossing the fracture site, the nails should not be directed toward posterior soft tissues to avoid damage to the radial nerve.
- One of the two nails must be rotated 180° to meet the biomechanical principle of FIN, which is based on the symmetrical bracing of two elastic nails.
- The surgeon must be familiar with bipolar retrograde and unipolar antegrade techniques to treat distal-third fractures.
- Careful trimming of nail ends and skin protection are critical.

13.8 FIN and Humeral Shaft Fractures: Postoperative Management in the Absence of Complications

Day 0	• Postoperative AP and lateral radiographs • Vascular and neurologic monitoring • Operated arm is elevated • Pain killers + antiinflammatories
Day 1	• Protective sling; patient is allowed to get out of bed
Days 2–3	• Discharge with instructions • Early return to school • Gentle mobilization of shoulder and elbow, everyday
Three weeks postop.	• Sling removed • Self-rehabilitation
Six weeks to four months postop.	• Clinical and radiological follow-up • Implant removal is considered • Return to sports
One year postop.	• Clinical and radiological follow-up

13.9 FIN Indications: Humeral Shaft Fractures



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14 Supracondylar Humeral Fracture

Pierre Journeau and Fabrizio Annocaro

14.1 General

14.1.1 Epidemiology

If one were to rank the most controversial fractures (the reputation, complication, and treatment methods of which have given rise to a number of publications, sometimes contradictory), the supracondylar fracture would probably rank first [1, 2]. As a matter of fact, this fracture, which is only seen in skeletally immature individuals, is by far the most common type of elbow fracture. Clavier [3] analyzed several series and said that elbow fractures (all types) accounted for 16% of all pediatric fractures, and that the incidence of supracondylar fractures varied according to authors (from 42 to 65%).

It usually occurs in the first decade of life with a peak incidence between the ages of 5 and 8 and prevalence in boys. The marked left-side predominance is difficult to analyze as no correlation has been found with the dominant or non dominant limb.

14.1.2 Mechanisms of Injury and Classifications

There are two types of supracondylar fractures based on the mechanism of injury (Fig. 14.1). The extension-type injury, with posterior tilt of the distal fragment, is the most common (Fig. 14.1a). It usually occurs after a fall on an outstretched hand with the elbow fully extended (indirect mechanism). According to some authors, the association of the natural elbow hyperextension in children between the ages 5 and 10, with decreased mechanical strength of the distal humeral metaphysis, might be a contributing factor [4]. During the fall, the wrist is hyperextended, and more importantly, the forearm is pronated so that if the elbow is extended, it is locked in this position. If the forearm remains supinated, the elbow does not get locked and bends upon impact. It is a common and well-known phenomenon in sports like judo and artistic gymnastics where the position of the forearm is predefined to lock or not the elbow during certain motions. The olecranon gets wedged in the olecranon fossa, and with loading fracture occurs at the weak point.

Posterior displacement has been classified by Lagrange and Rigault (French classification) [5] in five different types (Table 14.1):

- Type I: undisplaced. If the anterior cortex only is disrupted, it may be difficult to detect. On the lateral view, the presence of a hemarthrosis is revealed by a distended anterior capsule (the so-called "sail sign").
- Type II: unidirectional displacement (mainly posteriorly). Displacement angulation has no influence. Anteversion of the lower end of the humerus is lost due to posterior tilt. In Type II to Type V displacements, the anterior periosteum is completely torn, whereas posteriorly, the periosteal membrane is intact.
- Type III: multidirectional displacements including posterior tilt, translation, rotation, and coronal angulation. However, contact between bone fragments is maintained.
- Type IV: no contact between bone fragments irrespective of type and size of the displacement.
- Type V: meta-diaphyseal obliquely oriented fracture (downward and medially). Marked instability is a specific feature of this fracture.

P. Lascombes, *Flexible Intramedullary Nailing in Children,*
DOI: 10.1007/978-3-642-03031-4_14, © Springer-Verlag Berlin Heidelberg 2010

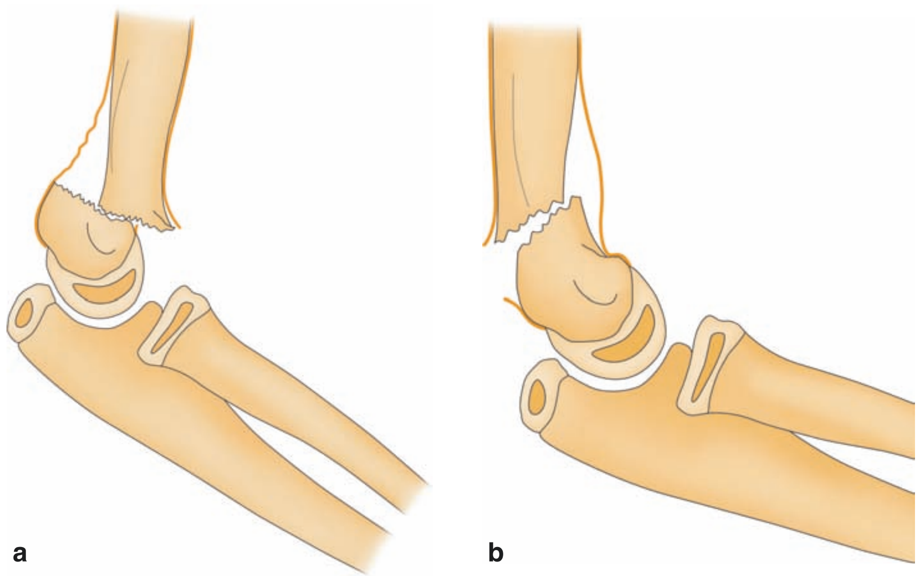


Fig. 14.1 (**a**) Type III extension fracture; (**b**) Type III flexion fracture

Among other classifications, the one developed by Gartland, which includes three types of fracture is the most widely used in the United States [4].

In these extension-type supracondylar fractures, the fracture line is usually concave as viewed in the coronal plane. It begins above the lateral epicondyle, passes through the olecranon fossa, and ends up above the medial epicondyle. As viewed in the sagittal plane, it is usually obliquely directed posteriorly/upwards [5]. In our experience, we have noticed that the more horizontal the fracture line, the lower the risk of secondary displacement (posterior translation). This must be considered when selecting the treatment method as some stable fractures can be successfully managed with non-operative treatment. In addition, it is important to assess the direction of the rotational displacement as it will influence the reduction maneuvers [6].

Flexion-type fractures (Fig. 14.1b) occur due to a fall onto a flexed elbow (direct impact), which results in anterior tilt of the distal fragment. They account for only 3–5% of all supracondylar fractures. The Lagrange and Rigault French classification can also be used for these fractures (i.e., Type I: no displacement to Type IV: no contact between bone fragments).

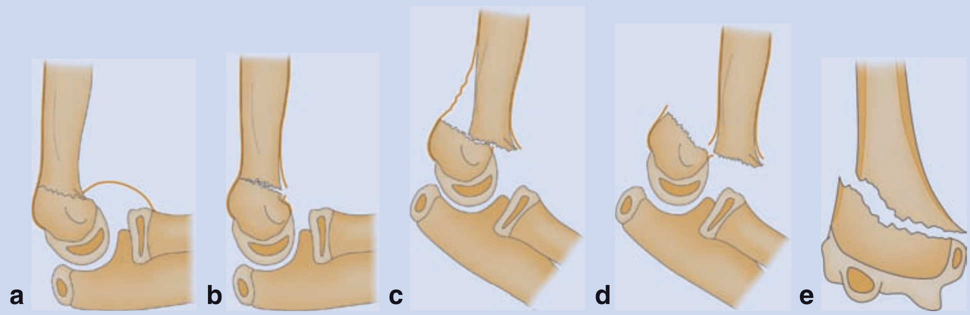
In both extension- and flexion-type supracondylar fractures, status of the periosteum on the concave side of the fracture (i.e., posterior periosteum in extension fractures and anterior periosteum in flexion fractures) is of paramount importance, as an intact periosteum ensures stability of the reduction. Unfortunately, there is no way of knowing the actual status of the periosteum before reduction is attempted. While healthy periosteum is always present in Type I and Type II fractures, it is much more uncertain in Type III and Type IV fractures.

Distal humeral epiphyseal separation is typically seen in very young children. It can result from a birth trauma, or it may indicate a battered child syndrome if it occurs in an infant. Arthrography can be helpful to visualize the distal humerus, which consists of unossified cartilage during the first 2 years of life, and to perform reduction (and subsequent immobilization).

As for any high-energy trauma, the early complication rate is quite high. In the Nancy series involving 217 fractures treated by flexible intramedullary nailing (FIN), we have had 70 early complications, including: neurovascular deficit, which is number one (57) and yet, in many cases, goes undetected [7]; protrusion through the skin (11); compartment syndrome (2). In 10% of the cases, these fractures are associated with other bone injuries, the most common of which are distal radial fracture and fracture of the distal one-fourth

Table 14.1 Lagrange and rigault classification [5]: extension-type fractures

Type	I	II	III	IV	V
Displacement	None	Posterior tilt	Contact maintained	No contact	Meta-diaphyseal fracture



of both bones of the forearm. This is why an X-ray covering the whole antebrachial region (Case 3) should be systematically taken.

14.2 Antegrade FIN Technique

The antegrade FIN technique we are describing here is for an extension-type fracture [8].

14.2.1 Anesthesia

This type of fracture is so painful that it is recommended to routinely use general anesthesia instead of regional anesthesia, which would require mobilization of the affected limb. Furthermore, general anesthesia allows neurologic monitoring as soon as the child awakens from anesthesia.

14.2.2 Patient Positioning

The child is positioned supine on a standard operating table with the injured upper limb placed on an attached radiolucent arm table. If the child has a short stature, which is often the case considering the young age of the patients who sustain these fractures, it may be helpful to place a small board parallel to the operating table to position the child closer to the arm table. This makes handling of the image intensifier much easier.

14.2.3 Image Intensifier

The antegrade technique is best performed with the use of two image intensifiers (where possible), which allow the surgeon to obtain simultaneously an AP and a lateral view without mobilizing the elbow. In this case, one image intensifier is placed parallel to the operating table at the level of the axilla, with the C-arm in a sagittal position, over the affected limb. The second image intensifier is oriented about 45° relative to the first one for an AP projection. The entire upper extremity is draped free to allow reduction in traction and lateral insertion of the nails at the deltoid V.

Reduction is checked with image intensification in both the AP and lateral planes, and with the elbow flexed and the shoulder placed in 90° of abduction and neutral rotation. The use of two image intensifiers eliminates the risk of inadvertent motions (Fig. 14.2).

14.2.4 Closed Reduction

Closed reduction should be systematically attempted to confirm reducibility of the fracture and make sure that open reduction is not required. Reduction maneuvers will be repeated intraoperatively.

For this initial reduction, the surgeon stands at the foot of the radiolucent table and applies longitudinal traction to the extremity. The assistant stands at the cleidocervical angle and applies a counter force to the brachial segment. It may be necessary to place an undersheet in the child's armpit and wind it up around the chest to use it as an additional counter brace. This way, counter-traction forces are evenly distributed (Fig. 14.3).

To achieve reduction, the surgeon holds the distal ends of both bones of the forearm with his/her hands and applies gentle traction, very slowly, to avoid stripping of the posterior periosteum. If the distal fragment is displaced in internal rotation, traction should be applied with the forearm supinated. If the distal epiphysis is displaced in external rotation, traction should be applied with the forearm pronated. Reduction of the distal fragment is checked using image intensification. The use of two image intensifiers eliminates the risk of inadvertent motions. Any minor displacement can be corrected by appropriate translation or varus/valgus maneuvers. Once correction is complete in all three planes, the surgeon maintains traction with one hand and grasps the distal humerus with his/her other hand, with the thumb placed on the olecranon. Then, the surgeon flexes the elbow while maintaining traction, and applies thumb pressure on the posterior aspect of the olecranon in order to return the distal epiphyseal fragment to its normal position. Counter force should be maintained by the assistant throughout the maneuver. Up to 120–130 degrees, elbow flexion should be achieved without effort. Difficulty in flexing the elbow indicates that reduction is inadequate. In this case, the whole maneuver must be repeated. Once the elbow is flexed, reduction can be maintained with the help of a simple tourniquet, which allows AP and lateral X-rays to be taken. If one image intensifier only is available, the C-arm is rotated to obtain both projections without rotating the elbow and loosing reduction.

The AP view shows alignment of the medial and lateral columns, and allows checking for correct Baumann angle (65–80°) [9]. The lateral view should allow visualization of an "hourglass" without an anterior metaphyseal beak that would indicate rotational malalignment, and/or allow assessment of correct lower end anteversion.

Fig. 14.2 Patient positioned supine. Injured upper limb placed on an attached arm table. Two image intensifiers

a

b

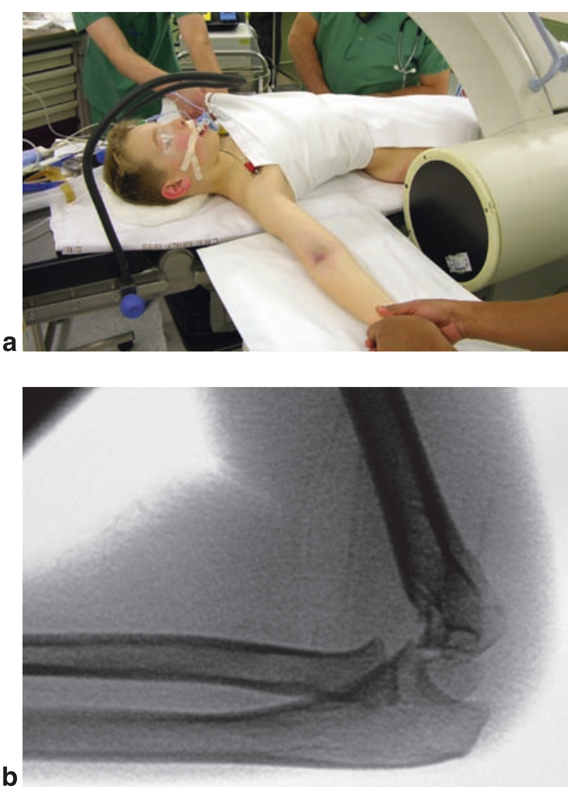


Fig. 14.3 (**a**) Initial reduction in extension using gentle longitudinal traction to the extremity. (**b**) Assessed by image intensifier in lateral projection

Once adequate reduction has been achieved, the surgeon must assess stability in both the anterior-posterior and medial-lateral planes. Micromotion, excessive opening of the fracture site, or a line that is obliquely directed posteriorly/upwards are considered contraindications to orthopedic treatment (e.g., Blount technique), and are perfectly amenable to antegrade FIN.

14.2.5 Operative Field

The entire upper limb is prepped. A sterile upper extremity drape is used, which covers the deltoid V and includes the lateral image intensifier. The upper part of the second image intensifier is covered with a sterile cap, and the C-arm is draped using a customized self-adhesive drape.

14.2.6 Selection and Preparation of the Implants

As for all epiphyseal fractures, sharp or tapered nails are routinely used to easily penetrate the dense cancellous bone of the distal humerus.

The most commonly used diameter is 2.0 mm, but it may vary from 1.5 to 2.5 mm depending on the age of the child. Care must be taken to select the implant size that matches the diameter of the medullary canal. As a matter of fact, advancement of sharp or tapered implants is quite difficult as they tend to catch on the walls of the canal. Therefore, contouring and bending are critically important. Mild contouring of the distal part of the nails greatly facilitates insertion into the medial and lateral columns of the distal humerus. The leading ends are slightly bent, just enough to be easily inserted through the entry point and smoothly take the turn without catching on the inner cortex.

Ideally, nails that have been specially designed for FIN should be preferred. Their gently curved tip facilitates insertion and advancement of the nail through the medullary canal. The beveled edge of the tip allows easy penetration of the epiphyseal bone.

14.2.7 Surgical Approach

Surgical approach is easiest with the surgeon standing at the cleidocervical angle and facing the two image intensifiers, and the assistant standing at the distal end of the table, that is, exactly the opposite of what is required to perform the reduction maneuvers.

A 15 mm (approximately) lateral skin incision is made over the deltoid V (Fig. 14.4), slightly more proximal than the anticipated entry points, so as to avoid skin impingement during insertion and advancement of the nails. Then, the surgeon inserts blunt scissors to feel the anterior and posterior aspects of the humerus to ensure proper location of the entry points on the lateral cortex. The hole is drilled using a drill bit that is slightly larger than the diameter of the nail; the drill is driven to the distalmost portion of the incision. During the drilling procedure, the surgeon must firmly maintain the humeral shaft with the other hand to avoid misdirection of the drill. Furthermore, integrity of the far cortex must be preserved. The hole is slightly elongated to an oval shape in the line of the long axis of the humerus to facilitate oblique advancement of the nail. The second hole is drilled just above the first one. The use of the awl is not recommended due to the potential risk of slippage on the cortical bone.

The first nail is attached to a T-handle and inserted into the medullary canal. Slight pronation movements will facilitate advancement of the sharp or tapered tip down such a narrow path. Sometimes, light hammer blows are even necessary. This first nail is advanced under fluoroscopic guidance toward the lateral column as far as the fracture site. The tip of the nail should point toward the distal fragment. The procedure is repeated for the second nail, which is inserted through the proximal hole and advanced past the isthmus. At the junction between the diaphysis and the distal metaphysis, the nail is rotated 180° to be advanced toward the medial column until it reaches the fracture site (Fig. 14.5).

14.2.8 Final Reduction

When both tips are properly positioned at the fracture site, the surgeon and the assistant change places. The

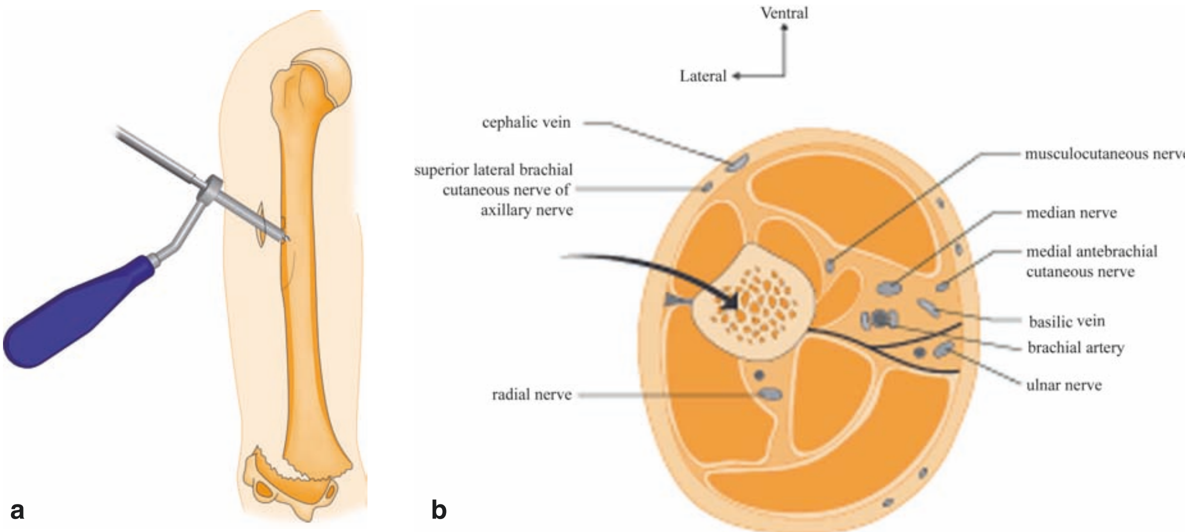


Fig. 14.4 (**a**) Skin incision and drilling over the deltoid V on the lateral aspect of the humerus, at the middle-proximal third junction; (**b**) transverse section through incision

surgeon stands at the distal end of the arm table and the assistant faces the humerus. The initial reduction maneuvers are repeated under fluoroscopic guidance while the assistant applies a counter force. Due to the poor remodeling capacity of the distal humerus, perfect reduction is mandatory.

14.2.9 Crossing the Fracture Site

With the nails properly positioned and after the perfect reduction has been confirmed, the assistant proceeds to impaction of the nails into the distal humerus, while the surgeon ensures that correct position is maintained at all times. This step is critical. Stray motions can be avoided by leaving the T-handle attached to the second nail once in position. This way, the assistant can safely impact the nail using a slotted hammer. Care must be taken to avoid producing a moment arm on the nail, which might result in rotational malalignment. The procedure is repeated for the second nail. As viewed in the coronal plane, the nails must follow the medial and lateral columns, whereas in the sagittal plane, both tips slightly point toward the midsection of the distal humerus.

It is essential to carefully assess the quality of the reduction prior to advancing the nails, as any malrotation, even minimal, will inevitably cause misdirection of the implants.

Once completed, the construct is so stable that the elbow can be unbent during fluoroscopic assessment to obtain a good AP view that allows to check for correct Baumann angle, thus confirming the absence of residual varus shift. The lateral view is helpful to assess stability of the construct in the anterior-posterior plane with the elbow in mid-flexion (Fig. 14.6).

14.2.10 Wound Closure

Both nail tips are slightly bent and trimmed to the desired length (so that they can be easily removed later on). As soft tissues in the deltoid V are quite thin, it is advisable to allow the nails to lie flush against the diaphysis to avoid the risk of skin impingement.

Then, the wound is closed in two layers without drainage.

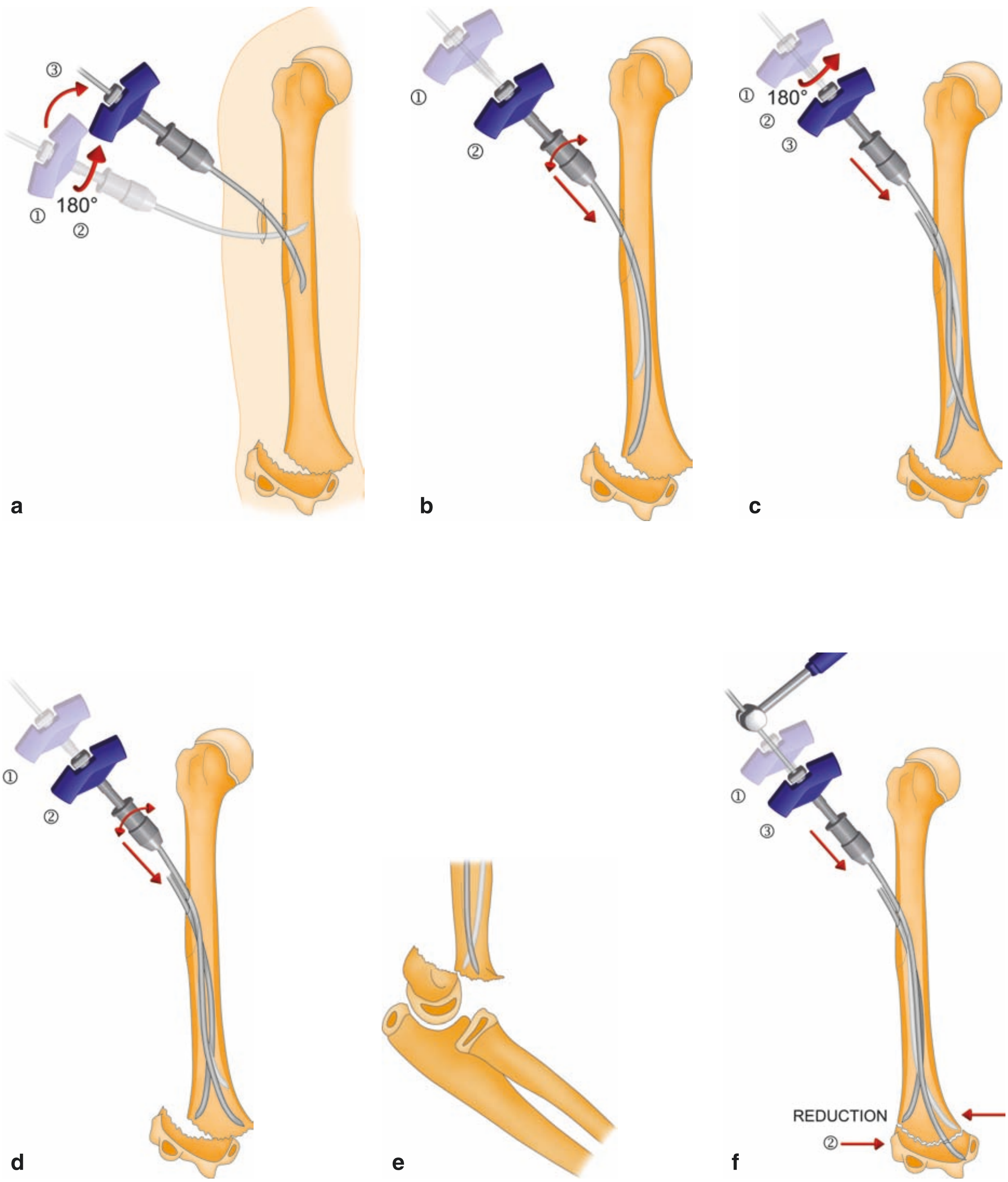


Fig. 14.5 Flexible intramedullary nailing (FIN) technique. First nail is inserted (**a**) and directed toward the lateral column (**b**). Second nail is inserted (**c**) and directed toward the medial column (**d**). In the lateral plane, both tips point towards the lower end of the humerus (**e**). Then, after the fracture has been reduced (**f**)

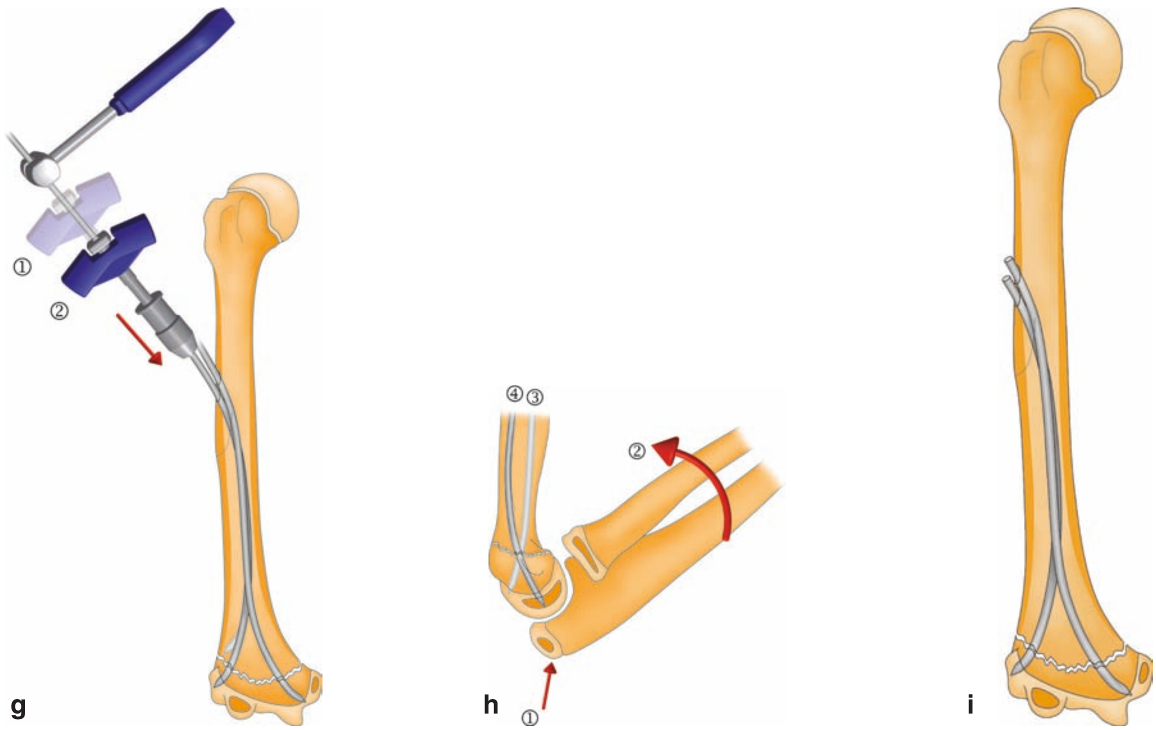


Fig. 14.5 (*cont.*) The nails are impacted into the distal humerus using a slotted hammer. AP view (**f**, **g**) and lateral view (**h**). Both tips are slightly bent and trimmed beneath the skin (**i**)

14.2.11 Flexion-Type Supracondylar Fracture

The reduction method is similar in its principle, but the maneuver is performed in the opposite direction: the surgeon slowly applies gentle traction to the forearm in order to pull down the distal fragment. After correct position has been confirmed by fluoroscopy, he/she slowly extends the elbow to return the distal fragment to its normal position. As for extension fractures, stability of the reduction essentially depends on the status of the periosteum (anterior periosteum). FIN is a good option in unstable fractures. Furthermore, it is a relatively straightforward procedure: entry points for the nails are located far away from the fracture site, and the implants can be advanced and impacted with the elbow extended (Fig. 14.7).

14.2.12 Postoperative Care

At the end of the procedure, a dry dressing is applied to the wound, a figure-of-eight bandage is used around the elbow joint to restrain flexion and extension, and the arm is immobilized in a sling. The bandage is left on for 48–72 h to allow edema to resolve.

AP and lateral X-rays are taken, and NSAIDs are prescribed for a few days.

Postoperative monitoring for 2–3 days is critical. It is focused on detection of compartment syndrome, monitoring of the radial, ulnar, and median nerves (including the anterior interosseous branch of the median nerve (AIN)), and assessment of local condition of the elbow joint. As a matter of fact, there may be severe local swelling, and the anterior skin bruising caused by the metaphyseal beak during the impact may progress toward necrosis.

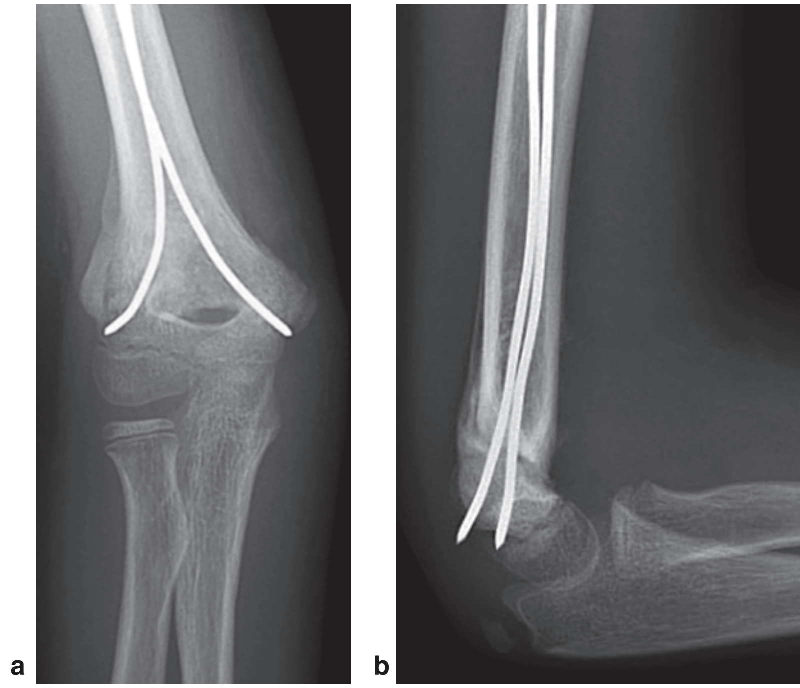


Fig. 14.6 A 10-year-old boy treated with antegrade FIN using two 1.8 mm tapered nails. Type IV extension supracondylar fracture was reduced anatomically. (**a**) AP view: Baumann angle is 70°; (**b**) Lateral view: the lower end of the humerus has normal anteversion

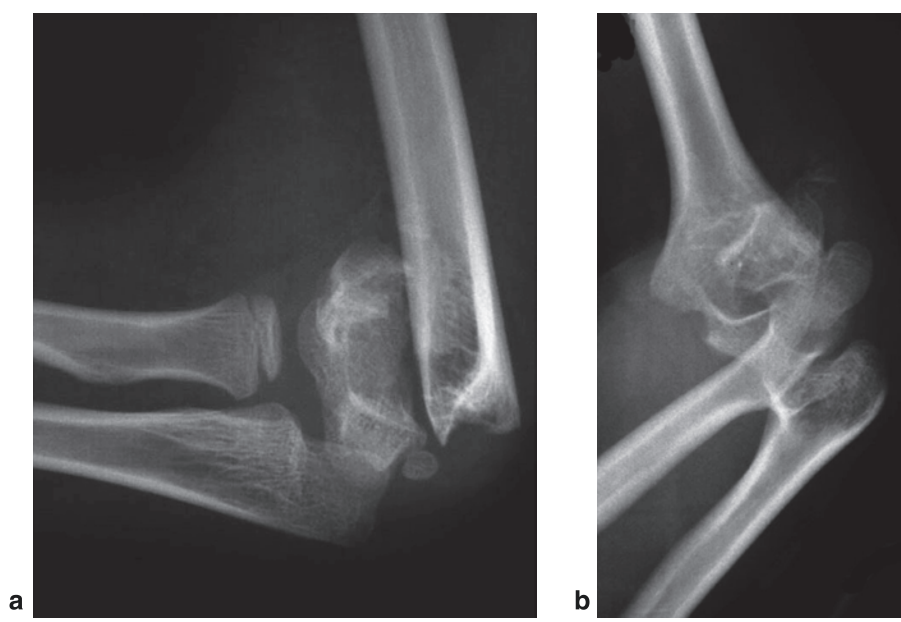


Fig. 14.7 A 9-year-old boy with a Type IV flexion supracondylar fracture sustained during judo activity, due to bad landing from a throw (**a, b**)

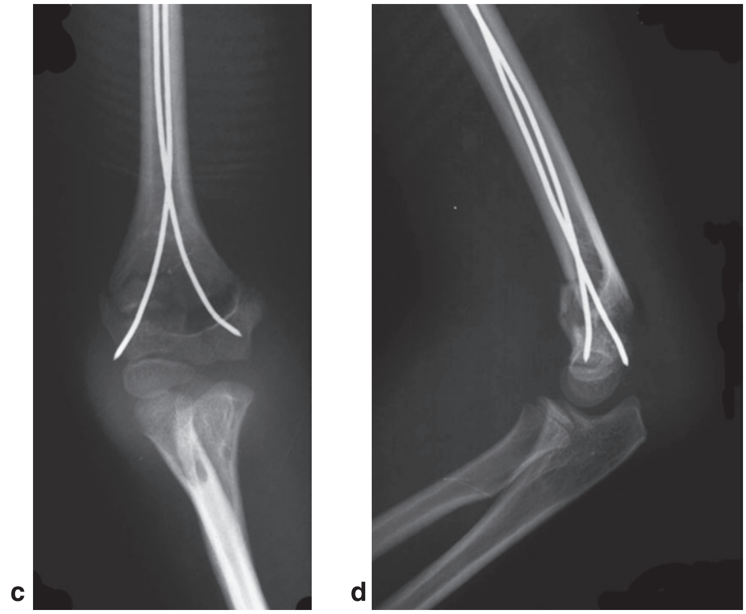


Fig. 14.7 (*cont.*) Unipolar antegrade FIN using two 1.5 mm tapered nails (**c, d**)

The child is allowed to get out of bed on Day 1 or Day 2, and will have to wear a protective sling for 3 weeks.

Passive mobilization and massages are proscribed as they may lead to the development of periarticular ossification.

14.2.13 Resumption of Activities

The child is usually discharged from hospital 2–3 days after surgery, and is allowed to return to school as soon as pain is gone, that is, between d5 and d7. The child is excused from sports and physical education for 3 months. The parents are instructed to remove the protective sling on the third postoperative week. Then, the child is allowed to resume activities of daily living, but violent movements are strictly prohibited. As a rule, self-rehabilitation is continued up to the 6-week follow-up date. The evaluation includes clinical examination and radiographic assessment based on AP and lateral views of the elbow. Should severe flexion contracture persist without any sign of progression after 1 month, an appropriate rehabilitation program should be considered, including active exercises against resistance.

14.2.14 Implant Removal

Nails are routinely removed the third postoperative month, even earlier, if skin impingement occurs, since healing time is short. Implant removal is performed under general anesthesia on a day-patient basis, using the previous scar.

14.2.15 Postoperative Follow-Up

The child must be followed both clinically and radiologically for approximately 3 years. Furthermore, the parents must be instructed about possible growth disturbances either due to central epiphysiodesis of the lower end of the humerus, leading to fish tail deformity, or due to varus/valgus malalignment.

14.3 Complications

14.3.1 *Complications Associated with this Type of Fracture*

14.3.1.1 Neurological Deficits

Neurologic complications may involve any of the nerves that course through the fold of the elbow. The radial nerve is mostly injured in medially displaced fractures, and the median and ulnar nerves in laterally displaced fractures. The anterior interosseous nerve (AIN) is frequently injured. The AIN is a purely motor branch that supplies the flexor pollicis longus and the flexor digitorum profundus. Injury to the AIN should be systematically sought. Function of this nerve is checked by asking the patient to flex the interphalangeal joint of the thumb and the distal interphalangeal joint of the index finger. These injuries are often unrecognized (50% of the cases, according to Louahem) [7]. If discovered after the operation, the physician-parents relationship may be severely compromised.

Therefore, accurate assessment of neurological injuries is essential preoperatively.

Most of the time, this type of paresis has a good prognosis provided that perfect fracture reduction has been achieved. A residual postreduction fracture gap and persistence of nerve palsy require surgical revision. As a matter of fact, nerve entrapment or nerve compression is not an uncommon complication, which predominantly involves the median nerve, but may also involve the radial nerve at the anterior metaphyseal beak. Involvement of the ulnar nerve is more often seen in flexion-type fractures, because it is stretched during displacement of bone fragments.

14.3.1.2 Vascular Complications

In most vascular complications, the radial pulse is absent but the hand is viable. In rare cases, the pulse is absent and the hand is ischemic.

In both situations, however, immediate reduction and fixation of the fracture should be performed in the operating room. Then, hand revascularization is evaluated. If normal return of a uniform color is noted, the patient must be closely monitored as the pulse may not be detectable for one or even 2 days. Beyond this delay, angiography becomes necessary to decide whether or not surgical reconstruction should be performed to avoid arterial claudication in spite of good vascularization of the hand [1] (Fig. 14.8). If ischemia persists after reduction, immediate exploration of the brachial artery at the fracture site must be performed for decompression or repair (most often using a venous graft).

When the fracture cannot be reduced by closed manipulation, which is rare, entrapment of a neurovascular pedicle may be suspected. In this case, an open approach is mandatory for decompression of the involved artery and/or nerve.

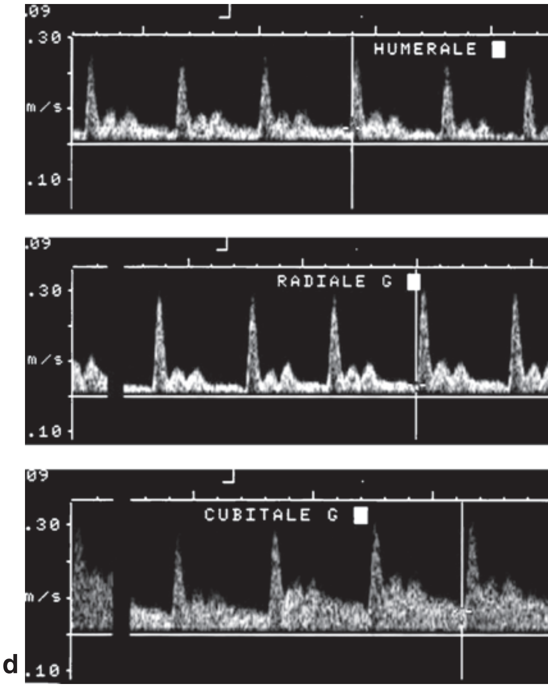
14.3.1.3 Skin Complications

Damage to the anterior skin in the bending area of the elbow is not rare. As a matter of fact, during the impact, the anterior metaphyseal beak violently hits all the structures located forward: muscles, sometimes neurovascular structures, and the skin. More or less severe bruises may occur and gradually progress toward necrosis. A more severe stage of complications includes protrusion through the skin, which we have encountered in 5% of our cases (Fig. 14.9).

a


Fig. 14.8 A 7-year-old girl with a Type IV supracondylar fracture sustained in a fall from her height, and ischemic hand (**a**)

b



d

c

Fig. 14.8 (*cont.*) Twenty-four hours after antegrade FIN, radial pulse was absent and capillary pulse was slow. Angiography showed occlusion of the brachial artery (**b, c**). A venous bypass was performed, and 1 year later, Doppler echography confirmed graft patency (**d**)

14.3.1.4 Compartment Syndrome

Although infrequent, compartment syndrome is a feared complication, which must be carefully sought. The surgeon must watch for any signs of an impending compartment syndrome. The significant decrease in the rate of occurrence of compartment syndrome is likely attributable to early institution of treatment. Rigault reported

Fig. 14.9 Protrusion of the fractured end of the bone in a Type IV supracondylar fracture of the *right elbow*. Severe bruising can be noted

a 3% incidence of compartment syndrome in 1962, whereas currently, the average rate is 0.5–1% (approximately) [7]. Contributing factors include: very high energy of the injury, magnitude of the displacement, absence of evacuation of the hematoma with management by closed means. In this respect, FIN facilitates monitoring since it does not need cast immobilization. Furthermore, the absence of cast avoids undesirable compression of the site.

When compartment syndrome occurs, the superior stability provided by FIN as compared to other internal fixation methods greatly facilitates fasciectomy and subsequent application of dressings.

14.3.2 Late Complications

14.3.2.1 Angular Deformities

Angular deformities are included in late complications because they can only be assessed after the fracture has healed and all ranges of motion have been restored. However, it must be pointed out that angular deformity is due to malunion, which most often results from inadequate initial reduction (Case 2), and sometimes from secondary displacement where fixation lacked stability. Of note: due to the poor remodeling capacity of the distal humerus, these frontal plane angular deformities are permanent and no improvement can be expected during the remaining growth period (Fig. 14.10).

The most common situation is varus malunion (cubitus varus deformity), knowing that the anatomic axes of the upper limb form a valgus angle of approximately 12° at the elbow joint, with significant variations according to age and sex [10]. The Baumann angle also needs to be measured, as it varies a great deal according to individuals, age and sex. Therefore, when a frontal plane angular deformity is present, it is recommended not only to measure these two angles, but also and above all to compare these values with those obtained from the contralateral side. Cubitus varus deformity is often accompanied by malunion with medial rotation. It is easily detectable on clinical examination as there is external rotation deficit of the shoulder. Cubitus valgus is a much less common deformity, which is often associated with excessive external rotation.

14.3.2.2 Joint Stiffness

Joint stiffness is not a concern until the end of the normal period of self-rehabilitation (several weeks). Moreover, active mobilization of the elbow joint is not recommended, at least during the first postoperative weeks. Actually, some degree of stiffness is commonly associated with treatment of supracondylar fractures. The surgeon should be wise enough to wait for spontaneous recovery of motion and resist temptation to refer the child to a physiotherapist too early. Also, massages, which are known to be responsible for the development of osteoma and periarticular ossification, and forceful manipulations, which lead to increased loss of range of motion due to inopportune nociceptive stimulation are proscribed.

However, should motion impairment persist longer than a few weeks post surgery, without any signs of improvement, the root cause must be investigated. Actually, the cause is often related to malunion. Extension malunion results in decreased anteversion of the lower end of the humerus and loss of flexion. Due to the poor remodeling capacity of the distal

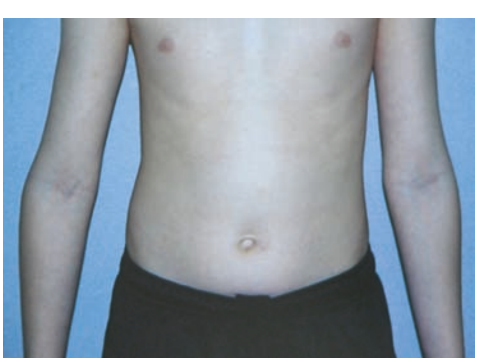
a

b


Fig. 14.10 Posttraumatic extension malunion: cubitus varus deformity of the *right elbow* (**a**), cubitus valgus deformity of the right elbow (in another child) (**b**). Note the interindividual variation in the anatomic axis

humerus, the amount of correction provided by growth is almost negligible (Fig. 14.11).

Another cause of stiffness is periarticular ossification, which acts as a stop either in flexion or in extension. However, as spontaneous favorable progression is commonly seen, physical therapy is not really necessary, and surgical excision should be used sparingly.

14.3.2.3 Growth Disturbances

Growth disturbances are very rare and are likely related to the development of ischemia in the lower end of the humerus due to displacement of bone fragments. Impaired blood supply results in central epiphysiodesis, leading to fish tail deformity (Fig. 14.12).

Fig. 14.12 Fish tail deformity resulting from posttraumatic central epiphysiodesis

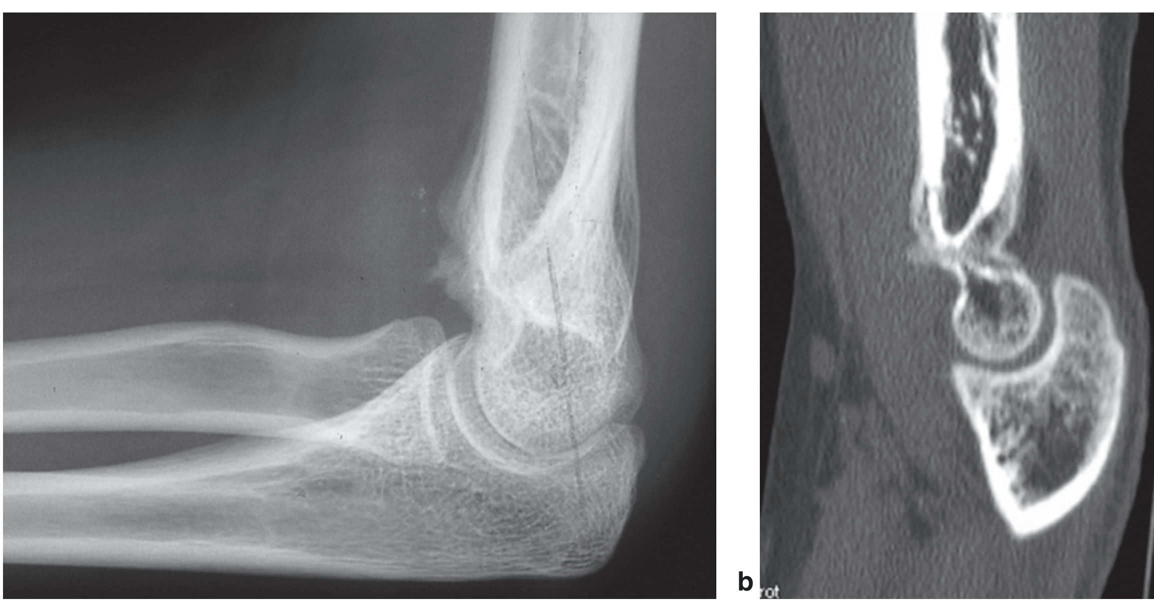


Fig. 14.11 Extension malunion: loss of normal anteversion (30–40°) of the lower end of the humerus. Range of flexion is limited to 100°. X-ray (**a**) and CT scan (**b**)

14.3.3 Complications Associated with this Technique

14.3.3.1 Neurovascular Complications

Although we have not experienced neurovascular complications so far, they cannot be ignored. Two areas are particularly at risk:

- The radial nerve located posterior to the humerus: during approach and during inadvertent slippage of an instrument.
- lThe brachial pedicle anterior to the humerus or medial to the humerus when drilling through both cortices.

14.3.3.2 Scar

The incision site is located in a highly visible area (particularly in girls). Furthermore, whatever the suturing technique, the scar may be broad and even hypertrophic. We started using surgical glue for dermal closure 3 years ago. It offers many advantages including water tightness, which allows the patient to take showers. However, it does not avoid scarring (Case 1), and some cases of skin allergy have been reported.

14.3.3.3 Implant-related Issues

Contrary to other types of fracture where swelling is so large that it may extend up to nail entry points, in supracondylar fractures, swelling never extends that far. When strictly adhering to the above technique, the incidence of skin irritation is extremely low.

14.4 Indications

FIN is one among other internal fixation options for the treatment of supracondylar fractures. It requires a certain amount of training, but it also offers clear-cut advantages. As a matter of fact, in addition to the high stability of the construct, which dispenses of the need for immobilization, correct insertion of the nails requires that perfect reduction is achieved, which minimizes the potential for initial malunion.

Whereas/Although Type I or II fractures are indisputably amenable to nonoperative treatment (cast or Blount technique), unstable Type III or IV fractures are elective indications. FIN has its place in the therapeutic armamentarium for extension and flexion-type fractures, with or without neurovascular disorders. It is also a valuable option in specific cases where close monitoring of the involved region is critical (e.g., vascular bypass), as it makes cast immobilization unnecessary.

14.5 Contraindications and Limitations

As for any closed reduction and percutaneous fixation technique, irreducibility is an absolute contraindication to FIN. If the fracture cannot be reduced by closed means, open anatomical reduction is necessary. Now, the choice of the most appropriate technical option can be discussed. Owing to the superior stability of the construct, FIN can be used in any situation, but it necessitates an additional approach for insertion of the nails so that pinning through the lateral epicondyle or cross-pin fixation may be more simple since the approach already exists.

14.6 Case Reports

14.6.1 Case 1

A 7-year-old girl fell off a swing and presented with a Type IV extension supracondylar fracture of the right elbow. There was no neurovascular or skin complication (a). An emergency FIN procedure was performed using two 2.0 mm nails. Initial reduction was judged satisfactory (b, c). Fourty-five days after surgery, union was achieved without secondary displacement (d, e), the child had recovered full range of motion, and the cosmetic appearance of the scar was highly satisfactory (f–h) (Fig. 14.13).

Fig. 14.13 Case 1

14.6.2 Case 2

An 8-year-old child operated on for a Type IV supracondylar fracture (a, b). The postoperative AP view clearly showed inadequate reduction and cubitus varus deformity, and the lateral view was falsely reassuring (c, d). At 6 weeks, varus angulation had increased; explanation was provided by the lateral view, which showed severe malrotation. One of the nails was not anchored in the epiphysis, which explains both the inadequate initial reduction and the progression of secondary displacement (e, f). Reasons for limited flexion were twofold: malunion, and impingement upon the nail that protruded anteriorly (Fig. 14.14).

Note: It is mandatory that both nails are anchored in the epiphysis.

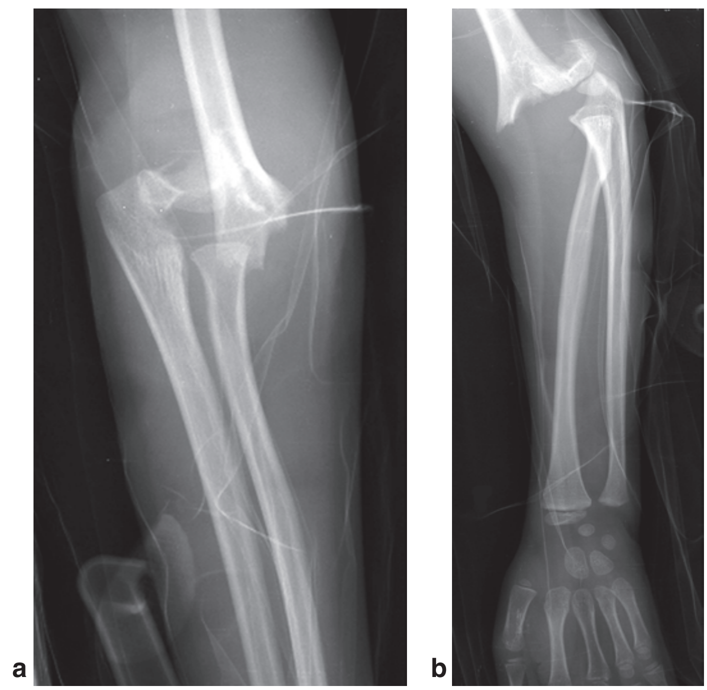
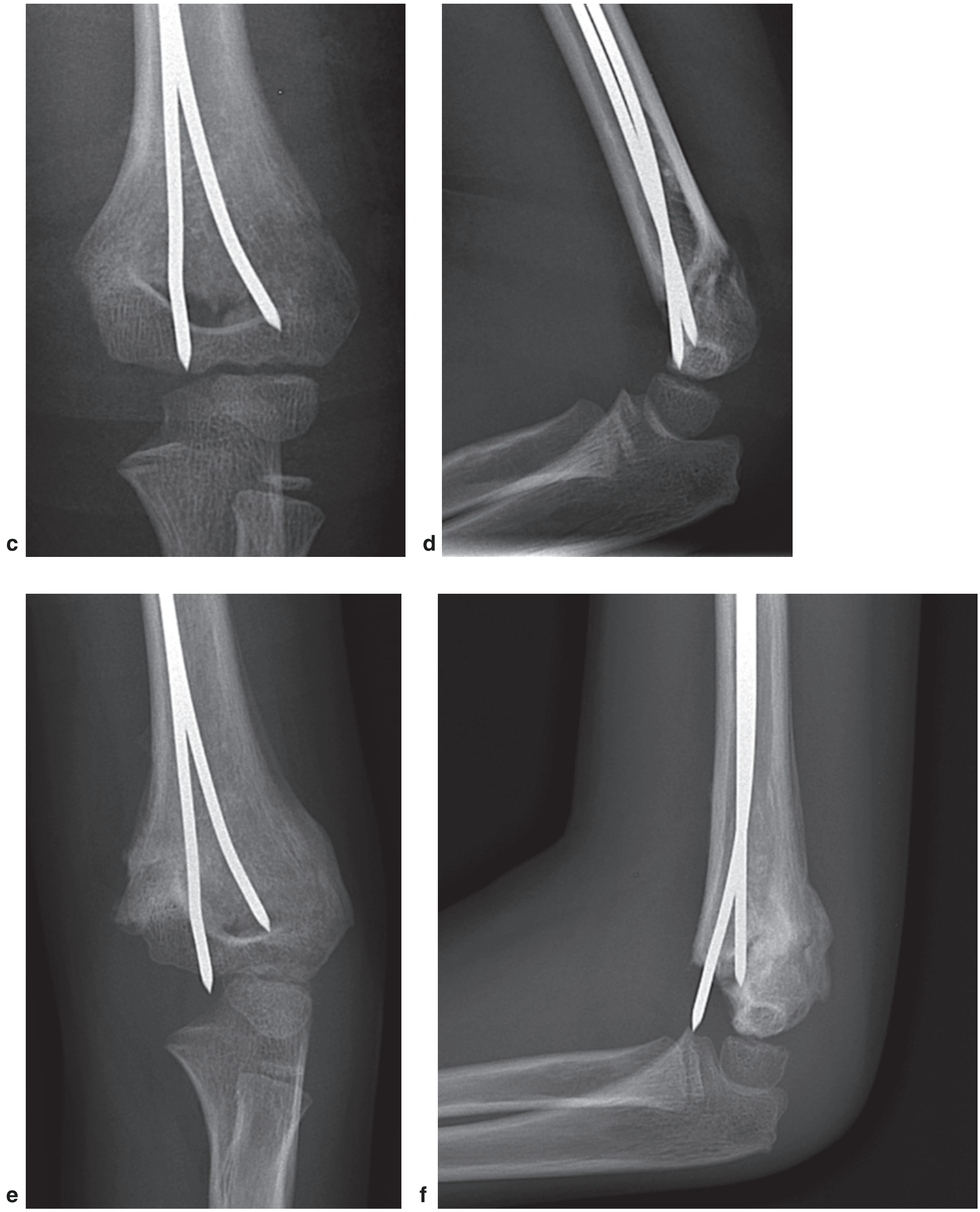


Fig. 14.14 Case 2



c d e f

Fig. 14.14 (*cont.*) Case 2

14.6.3 Case 3

A 4-year-old child fell from a height and presented with a Type IV supracondylar fracture associated with a distal radius fracture (a, b). Treatment consisted in FIN using two 1.5 mm tapered nails (c, d), reduction of the wrist joint (e), and immobilization in a long-arm cast for 4 weeks. At 3 months, the result was excellent (f, g) (Fig. 14.15).

Note: One must bear in mind that in 10% of the cases, the supracondylar fracture is associated with a distal radius fracture.

Fig. 14.15 Case 3

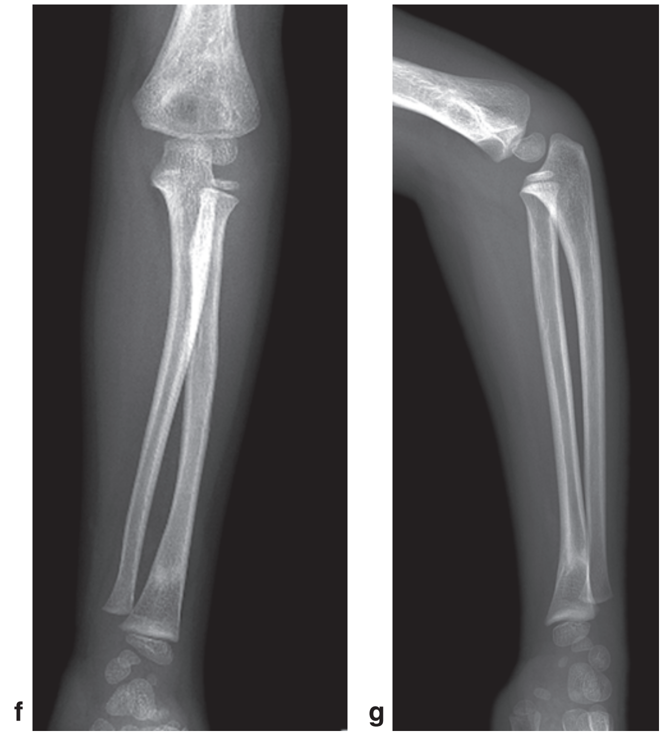


Fig. 14.15 (*cont.*) Case 3

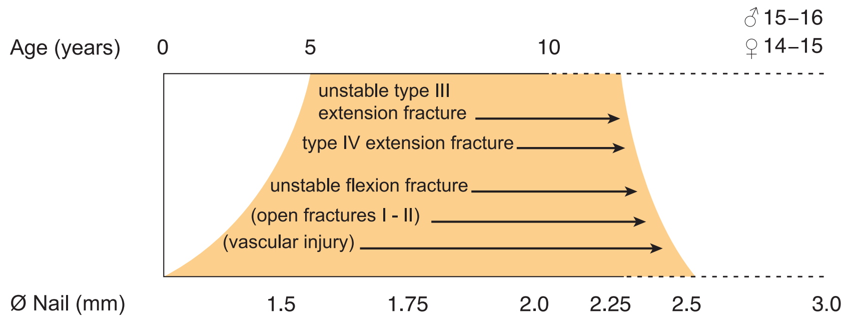
14.7 Six Key Points

- Two 1.5–2.5 mm diameter nails with a tapered end should be used (dense epiphyseal bone).
- The two nails should be directed toward the lateral and medial columns, respectively.
- Both tips should point toward the lower end of the humerus (reduced) in both AP and lateral planes.
- Fracture reduction should be performed and checked using two image intensifiers.
- Both nails should be impacted into the epiphysis using a slotted hammer (one single try).
- Distal position of the nails and stability of the construct should be carefully checked.

14.8 FIN and Supracondylar Humeral Fracture: Postoperative Management in the Absence of Complications

Day 0	• Postoperative AP and lateral radiographs through dressing • Vascular and motor monitoring • Operated arm is elevated • Pain killers ± antiinflammatories
Day 1	• Protective sling; patient is allowed to get out of bed
Days 2–3	• Discharge with instructions • Early return to school
Three weeks postop.	• Sling removed • Self-rehabilitation
Six weeks to three months postop.	• Clinical and radiological (AP and lateral) follow-up • Nail removal is considered • Return to sports
One to three years postop.	• Clinical and radiological (Ap and lateral) follow-up

14.9 FIN Indications: Supracondylar Humeral Fractures



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Radial Neck Fracture

15

Pierre Journeau and Nicolas Moh-Ello

15.1 General

15.1.1 Epidemiology

Radial neck fractures are very infrequent in children; actually, they only account for 1% of all fractures and 5–14% of elbow fractures. They involve all age groups from childhood to prepuberty, with a peak incidence at around 9–10 years of age. They occur at a younger age in girls than in boys (approximately, 2 years earlier) [1].

15.1.2 Mechanisms of Injury and Classifications

The mechanism of injury is usually an indirect one. It results from a hard fall on an outstretched hand in which the elbow is extended or slightly flexed and a valgus force is applied to the elbow joint. According to the Jeffery classification, which is based on the mechanism of injury, it is a Type I injury. The head of the radius is driven against the capitulum. As the radial head is essentially cartilaginous, it is more resistant to trauma; this is why isolated radial head fractures and epiphyseal separations are so rare. Typically, the proximal radial metaphysis cannot withstand the sudden axial compression forces to which it is subjected and breaks.

Another mechanism is fracture of the radial neck associated with dislocation of the elbow: it is a Jeffery Type II injury [2]. It may occur during posterior dislocation of the elbow, and in this case, the radial head remains in an anterior position [3]. It may also occur during reduction of the dislocation, and in this case, the radial head will remain posteriorly dislocated (posterior to the capitulum). This form of fracture adversely affects the prognosis because of the associated vascular risk, not to mention the fact that the procedure itself is significantly more challenging.

There are two anatomic types of radial neck fracture. The most common is by far the pure metaphyseal fracture of the radial neck with subsequent Salter II epiphyseal separation. The other types of epiphyseal separation, particularly those with intra-articular fracture extension (Salter Type III and Type IV) are exceptional.

Associated injuries are frequent, from fracture of the olecranon, which occurs in an extended elbow, to dislocation of the elbow joint with or without avulsion of the medial epicondyle in an elbow that is slightly flexed at impact. But skin lesions and neurovascular injuries are exceptional.

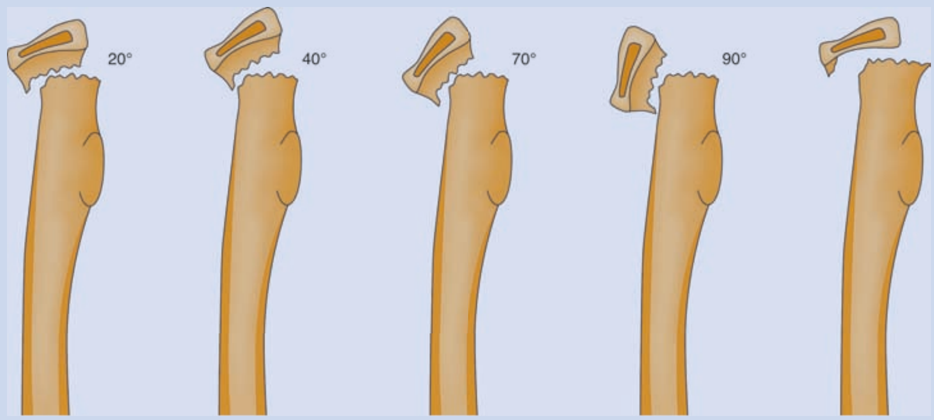
Many classifications have been developed for radial neck fractures. All of them are interesting in their own way: Jeffery classifies according to the mechanism of injury; Judet combines translation and type of fracture in its classification system (the earliest one); Métaizeau classifies according to translation and influence on prognosis (Table 15.1) [4]. Wilkins classification, which combines mechanism of injury and anatomic type of injury, has no prognostic value, and is therefore seldom used in France [1].

During displacement, a metaphyseal periosteal flap often remains attached to the radial head. Preservation of this sleeve, which contributes to the vascular supply to the radial head, is critically important for two reasons: first, to preserve the blood vessels it contains and second, because once tensioned, this piece of tissue will assist in maintaining the reduction (Fig. 15.1).

P. Lascombes, *Flexible Intramedullary Nailing in Children,*
DOI: 10.1007/978-3-642-03031-4_15, © Springer-Verlag Berlin Heidelberg 2010

Table 15.1 Judet classification with Métaizeau modification

Grade	I	II	III	IV	V
Radial head angulation	<20°	20–45°	45–80°	>80°	Epiphyseal separation
Translation	<3 mm	<50%	>50%	>100%	



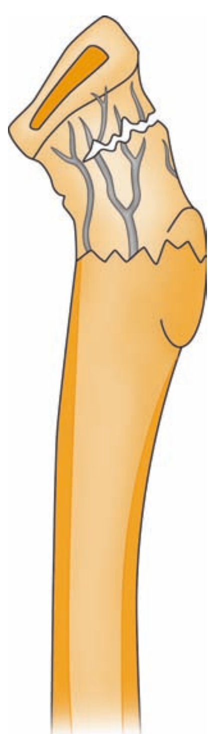


Fig. 15.1 Translation most often occurs in the posterolateral direction, leaving an intact periosteal hinge at the angulation. This hinge acts as a vascular carrier which maintains vascularity of the epiphysis

15.2 Retrograde FIN Technique

15.2.1 Anesthesia

As is often the case in trauma surgery, retrograde FIN (flexible intramedullary nailing) [5, 6] should be preferably performed under general anesthesia instead of regional anesthesia for ease of postoperative monitoring (one compartment syndrome was reported in the Nancy series). Furthermore, reduction is best achieved with the patient under general anesthesia as it permits complete relaxation of muscles.

15.2.2 Patient Positioning

The child is positioned supine on the operating table with the injured upper limb placed on an attached radiolucent arm table. A tourniquet is placed at the upper arm. It is not systematically inflated but it may prove useful should open reduction be required.

15.2.3 Image Intensifier

An image intensifier is usually placed parallel to the operating table and perpendicular to the arm table, at the level of the child's axilla. In this position, the surgeon can face the image intensifier and the posterolateral compartment of the elbow, and has a straight-shot access to the radial head and an easy access to the distal radial metaphysis. The assistant stands at the end of the arm table, perpendicular to the surgeon, and performs the traction-reduction maneuvers. Reduction is performed under fluoroscopic guidance. For the AP projection, the elbow is extended in a mid-pronation position. For the lateral projection, it is flexed 90° in a mid-pronation position, and the shoulder is positioned in full external rotation. This avoids repeated manipulation of the forearm in pronation-supination, which might compromise the stability of the reduction (Fig. 15.2).

15.2.4 Operative Field

The entire upper limb is prepped. A sterile upper extremity drape is used, which extends down to the tourniquet, and covers the child's body, including the trunk and the lower limbs.

15.2.5 Closed Reduction

Once prepping and draping are completed, closed reduction is attempted. As a matter of fact, the FIN technique is used either to stabilize the reduced fracture or (and this is the most common) to reduce and stabilize the radial neck.

Fig. 15.2 Injured *upper limb* is placed on an arm table, with image intensifier placed at the level of the child's axilla

Two different reduction maneuvers can be used, but prior to anything else, the surgeon must determine the plane of maximal displacement of the radial head. This is achieved using image intensification at progressively larger angles, from supination to full pronation. The plane of maximal displacement is found when the radial head forms an almost perfect rectangle, with a clearly and entirely visible physis. It is generally translated in the posterolateral direction, so that the plane of maximal displacement is best visualized in 20–40° of pronation (with reference to a full supination position).

The first maneuver was described by Patterson: the assistant places a varus stress on the extended elbow and applies traction to restore the joint space [7], while the surgeon places his/her thumb on the assumed position of the radial head (i.e., in the plane of maximal displacement) and gives a firm push in an upward and medial direction to return the radial head to its normal position. In this method, the forearm is supinated, but many variants have been designed. According to other authors, the elbow should be slightly flexed for better muscle relaxation. Jeffery recommends a small amount of pronation of the forearm to ensure that the push is applied in the plane of maximal displacement.

For the second maneuver, the thumb is replaced by a punch. It is important to place the punch on the radial head, not on the radial neck, in order to avoid damage to the blood vessels, which run through the periosteal flap. Correct position for the punch is determined using image intensification. The elbow is positioned in mid-flexion and slight pronation to allow forward shift of the radial nerve, which courses around the radial neck. This minimizes the risk of damaging the radial nerve with the instrument (Fig. 15.3). A simple lever movement helps reposition the radial head to assess stability. If stability is satisfactory, the upper limb is immobilized in a long-arm cast with the elbow flexed 90° and the forearm pronated. If it is not satisfactory, intramedullary nailing is necessary [8].

15.2.6 Selection and Preparation of the Implants

Sharp or tapered stainless steel or titanium nails are used as they literally pin the epiphyseal-metaphyseal fragment, and provide a firm anchorage during the

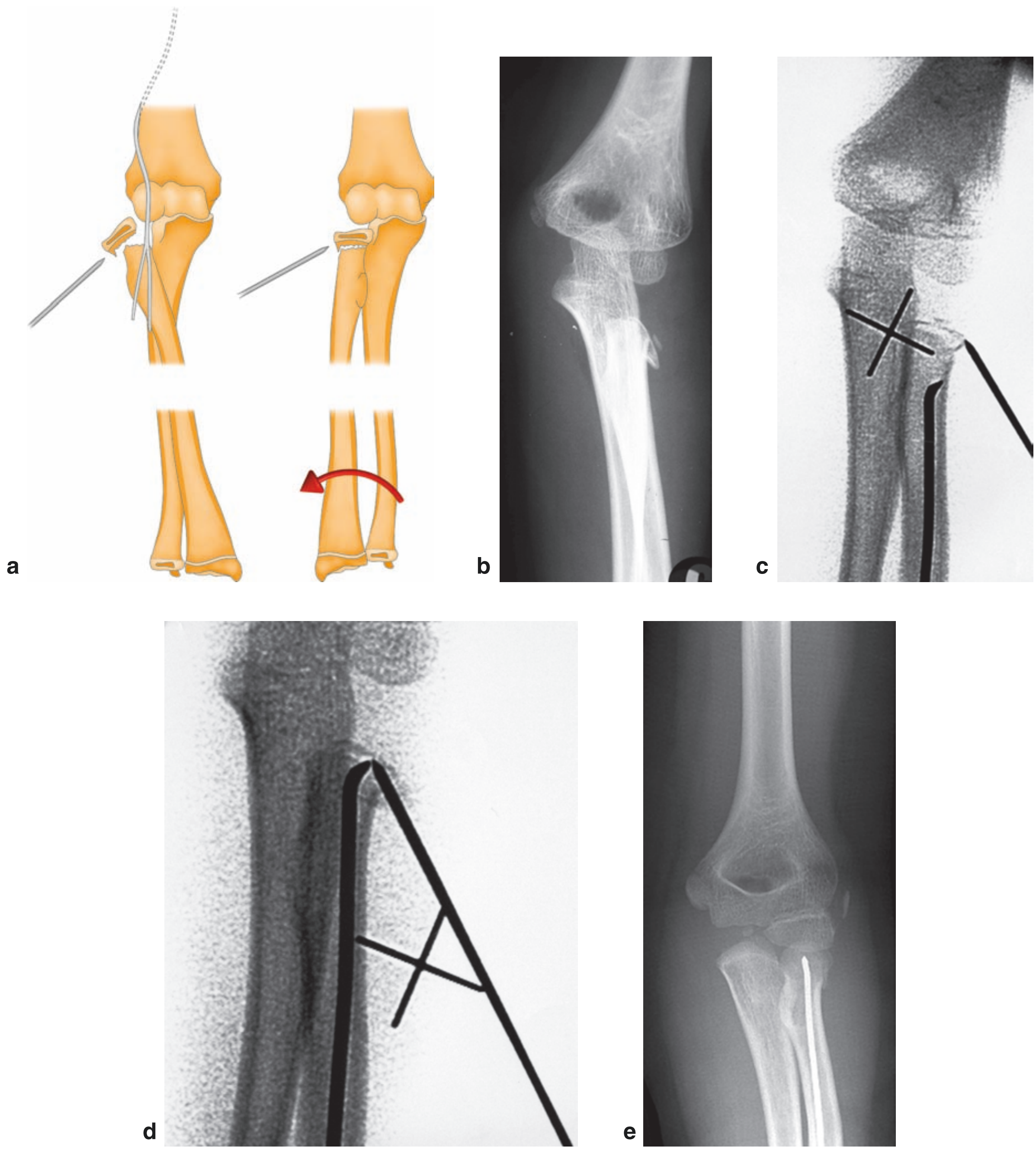


Fig. 15.3 Use of a punch: the forearm is pronated to allow forward shift of the radial nerve and thus protect it from injury. The punch is placed on the epiphysis, not on the radial neck, in order to avoid potential damage to the precarious vascularization (**a**). Clinical case: a 5-year-old girl with a Type IV fracture (**b**); (**c**) nail is pushed upwards while the radial head is reduced with the help of the punch; (**d**) nail enters the epiphysis and reduction is maintained with the punch; (**e**) result at 3 years follow-up

reduction maneuvers. Blunt-tipped nails may not penetrate the dense cancellous bone and instead push the fractured fragment. Nails with a tapered tip combine two advantages: sharpness for easy penetration of the epiphysis, and flatness for increased trabecular support and easier fracture reduction. Furthermore, stainless steel has a lower elastic modulus than titanium, which facilitates rotational maneuvers.

The most commonly used diameter is 2.0 mm, but it may vary from 1.5 to 2.5 mm depending on the age of the child.

If a straight nail is used, the tapered leading end must be slightly bent to anchor in the fractured fragment. Mild contouring is performed in the same plane and direction as the tip to match the natural curve of the radius at the end of the procedure.

15.2.7 Surgical Approach

The skin incision is made on the lateral aspect of the metaphysis of the distal radius, 10 mm distal to the anticipated entry point. This avoids the risk of skin impingement during oblique insertion of the nail (see Chap. 16).

Identification of the distal physis with fluoroscopy assists in accurately positioning the 15–20 mm longitudinal incision. Blunt scissors dissection is then performed. The radial vein and the sensory branch of the radial nerve are successively retracted posteriorly and protected with a mini retractor. Dissection continues anterior to the insertion of the brachioradialis tendon to avoid potential damage to the extensor pollicis brevis and abductor pollicis longus tendons, and is carried down to the bone (Fig. 15.4).

The entry hole is made with an awl in the same anterior posterior oblique direction, 10–15 mm above the distal physis. Care should be taken not to slip anteriorly to avoid injury to the radial artery. The chief advantage of this anterolateral approach to the distal radius is safety as there are no critical superficial neurovascular structures in the vicinity. Furthermore, if the

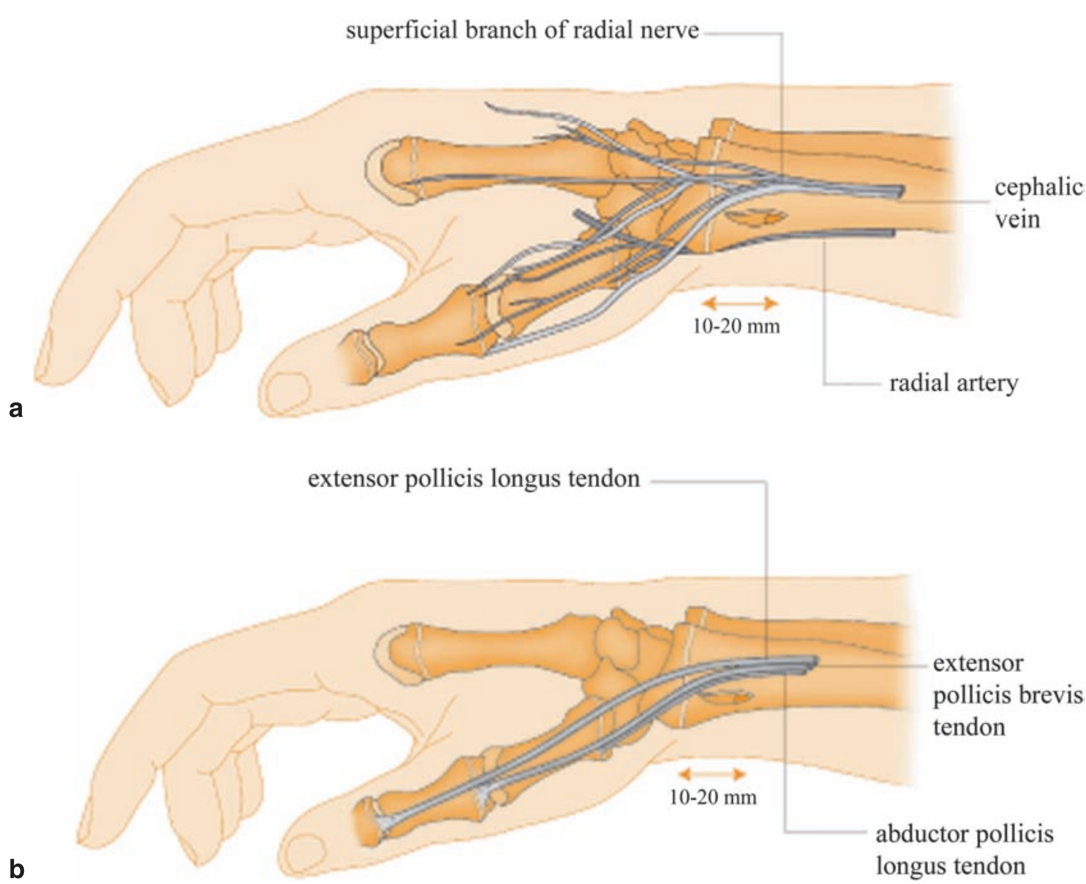


Fig. 15.4 Entry hole is created in the distal radial metaphysis. A 15–20 mm longitudinal incision is made anterior to the intermediate antebrachial vein and the sensory branch of the radial nerve. (**a**) The hole is made in an anterior-posterior direction to avoid injury to the radial artery; (**b**) position of the entry hole: 10–15 mm above physis, on the anterolateral aspect of the distal radius, anterior to insertion of the brachioradialis tendon and anterior to extensor pollicis tendons

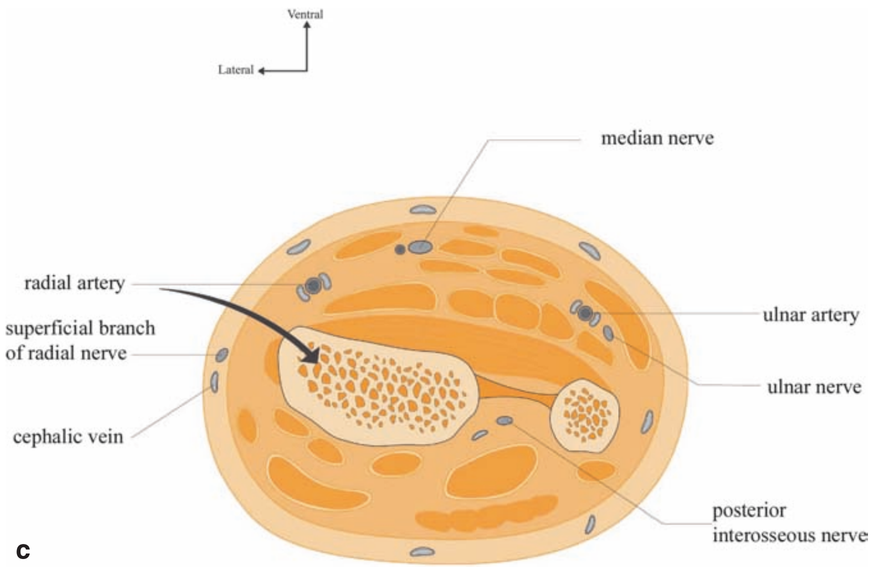


Fig. 15.4 (*cont.*) (**c**) Transverse section through incision

metaphysis is firmly held in mid-pronation with the thumb and index finger, the awl can be safely directed posteriorly, opposite the radial artery (Fig. 15.5).

The nail is attached to a T-handle and inserted into the medullary canal. Advancement of a tapered implant through such a narrow path may be somewhat difficult, and slight pronation movements or even light hammer blows may be necessary. Following the natural curve of the radius facilitates initial advancement of the nail.

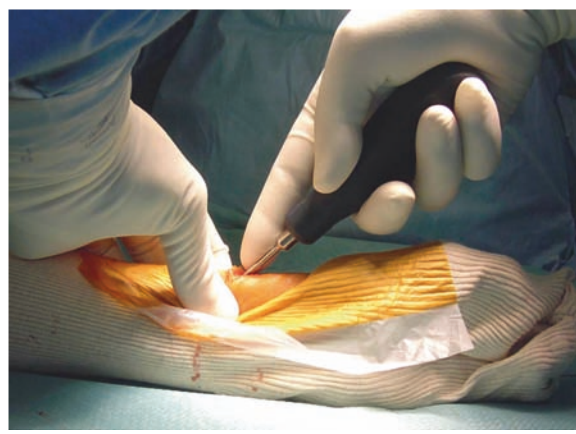


Fig. 15.5 Surgeon firmly holds the distal metaphysis in mid-pronation with the *thumb* and *index finger* while directing the awl in a slightly oblique posterior direction

15.2.8 Crossing the Fracture Site

Once the nail has reached the fracture site, it must be rotated so that its tip is positioned right in front of the radial head, in the plane of maximal displacement. The nail is firmly impacted into the radial head under fluoroscopic guidance using heavy hammer blows. Then, reduction of translation and tilt is obtained by rotating the nail 180° anteriorly. In fact, direction of the rotation depends on the position of the radial head, but as the radial head is most often translated postero-laterally, rotation is performed in an anteromedial direction. Therefore, with the surgeon facing the distal end of the radius, rotational movement will be clockwise in a right elbow and counterclockwise in a left elbow (as for testicular reduction in testicular torsion repair). Gentle rotation is mandatory, otherwise the tip of the nail may cut out into the epiphysis. It is also recommended to combine rotation of the nail and pronation of the forearm. In fractures with grade 4 displacement, it may be necessary to use a punch as previously described to gently move the radial head toward the nail until it is positioned right in front of the nail tip (Fig. 15.6).

15.2.9 Final Reduction

Once closed reduction is completed, the tip of the nail should be directed medially and follow the natural curve of the radius. This means that after reduction and stabilization have been achieved, further manipulation will result in secondary displacement (Fig. 15.7).

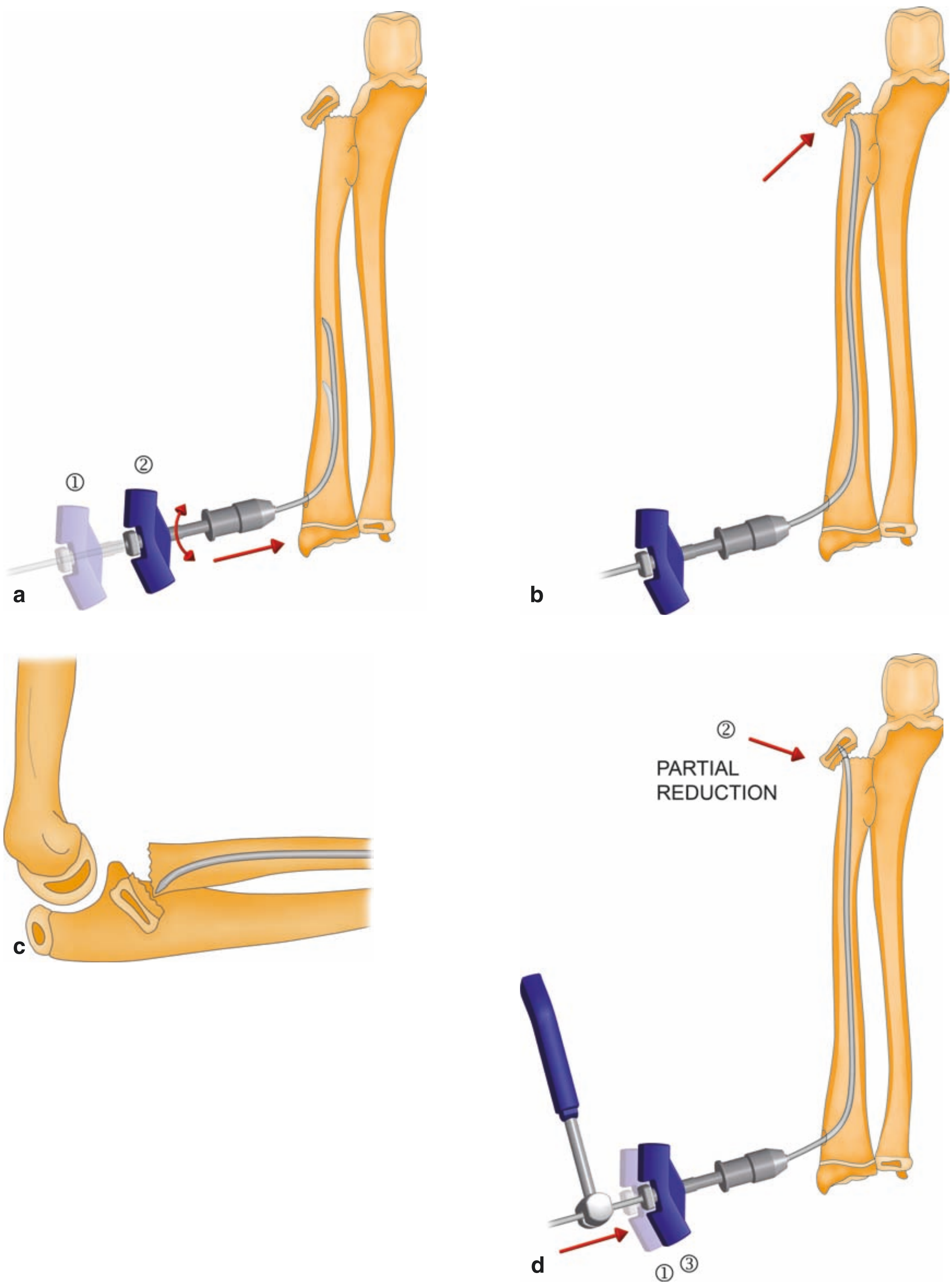


Fig. 15.6 Flexible intramedullary nailing (FIN) for radial neck fracture: (**a**) intramedullary nail is slowly advanced with the aid of slight rotatory movements (clockwise and counterclockwise) of the T-handle. Tip of the nail reaches the fracture site laterally (**b**) and posteriorly (**c**). During this time, the surgeon tries to reduce the radial head as much as possible by applying digital pressure; (**d**) then, the nail is impacted into the radial epiphysis using a slotted hammer

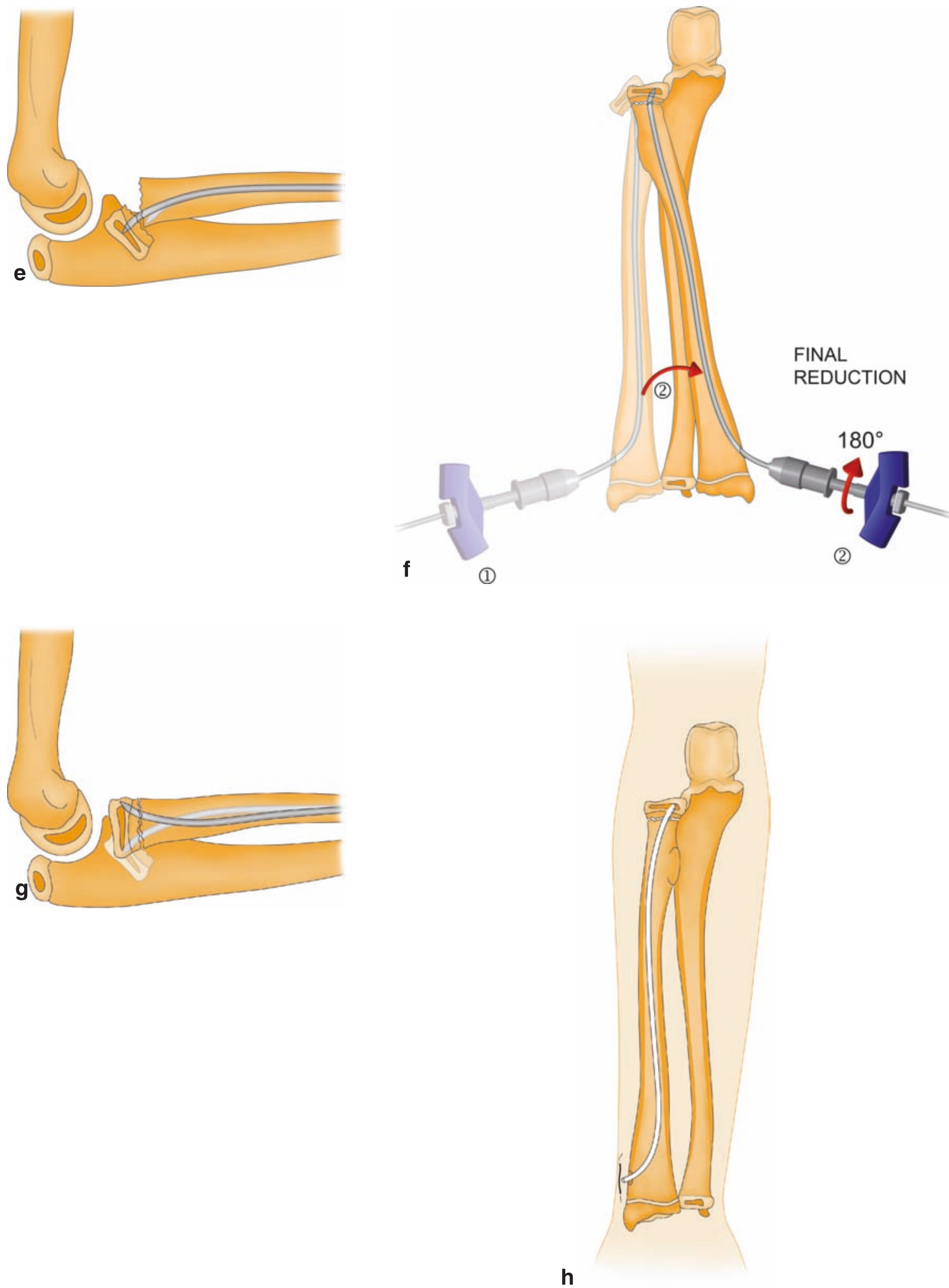


Fig. 15.6 (*cont.*) (**e**) Then, the nail is impacted into the radial epiphysis using a slotted hammer; (**f, g**) finally, reduction is performed by combining rotation of the T-handle and pronation of the forearm; (**h**) reduction and stabilization are now achieved

Owing to the remodeling capacity of the radial neck and depending on the child's age at the time of surgery, under reduction (lateral tilt) of up to 20° and even 30° is acceptable [9]. Therefore, we think that one should not try at all costs to achieve a perfect reduction at the risk of damaging the lateral periosteum or making multiple perforations in the radial head.

15.2.10 Wound Closure

At the end of the procedure, the trailing ends of the nails are slightly bent to keep them at a distance from the bone, and carefully trimmed using cutting pliers to make a clean cut that will not cause injury to the subcutaneous tissues. Only 3–5 mm should protrude out of the bone to facilitate later removal. In case of excessive protrusion, the use of an impactor may be necessary to recess the nail ends. The wound is closed without drainage and a compressive dressing is applied (Chap. 16, Fig. 16.7).

Alternatively, the distal end can be left unbent, and just cut using its elastic properties. Once trimmed, it will spring back and lie flush against the metaphysis, thus avoiding impingement upon critical structures.

Then, the wound is closed in two layers without drainage.

15.2.11 Types of Radial Neck Fractures

15.2.11.1 Type IV

These fractures cannot be managed straight away with FIN as the severe radial head tilt precludes impaction of the nail. The first technical option is to use a punch to partially reduce the radial head and allow insertion of the nail [8].

The second option is to perform a step-by-step reduction: first, the nail is impacted into the radial head and reduction is attempted by rotating the nail. If reduction is insufficient, the nail is freed by applying a firm hammer blow to avoid the risk of secondary displacement, and the impaction/rotation procedure is repeated to complete the reduction (Fig. 15.8).

Now, a third option is available, which consists of inserting a provisional nail to both partially reduce and stabilize the fracture. Then, a second nail is inserted in the same way, which will anchor in the partially reduced epiphysis. The provisional nail can then be removed, and reduction is completed using the second nail. The main drawback of this method is the creation of two distal holes, and its major limitation is the small diameter of the medullary canal, which may not accommodate both nails [6].

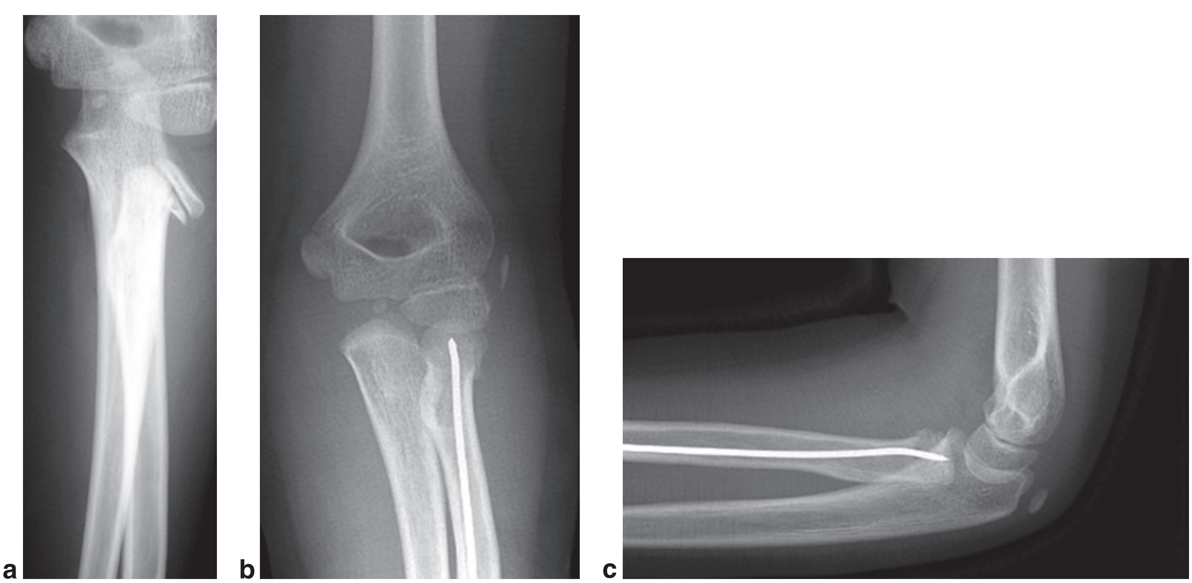


Fig. 15.7 A 9-year-old girl with a Type III epiphyseal separation of the radial neck: AP view (**a**). Immediate postoperative result of retrograde FIN performed with a 1.5 mm nail (**b, c**)

a b c d

Fig. 15.8 An 11-year-old girl with a Type IV radial neck fracture (**a, b**). Retrograde FIN with a 1.5 mm tapered nail and anatomical reduction (**c, d**)

15.2.11.2 Radial Head Dislocation

Dislocation of the radial head anterior to the capitulum is not a contraindication to the FIN technique, which can still be used, but with extreme caution. The main hazard is misdirection of the nail, which may cause injury to the anterior structures. We strongly advise surgeons against the use of a punch in anterior dislocation cases because of the high risk of injury to the radial nerve. The main difficulty lies in evaluation of the plane of maximal displacement to correctly perform the reduction maneuvers.

Dislocation of the radial head posterior to the capitulum is a contraindication to percutaneous reduction because of the risk of 180° rotation of the radial head, which would result in avulsion of the periosteal flap (if present) and, as a consequence, in necrosis of the epiphysis (Case 1).

A posterolateral approach is used between the extensor carpi radialis, anteriorly, and the extensor digitorum, posteriorly. A technical trick from Métaizeau's personal technique consists in using a lateral approach through a superolateral arthrotomy, which will afford access to the radial head from above, and will reduce the potential risk of injury to an already weakened periosteal flap. Caution must be exercised when mobilizing the radial head, in order to preserve integrity of the few blood vessels that remain. Once reduction has been achieved, stabilization is provided by intramedullary nailing as previously described, or sometimes sutures are placed through capsuloperiosteal tissue [10].

15.2.12 Postoperative Care

At the end of the procedure, range of motion is carefully evaluated in pronation-supination. Image intensification is used to assess stability of the fixation.

A dry dressing is applied to the distal wound, and the upper extremity is immobilized in a long-arm cast (traditional plaster or more often resin) in slight pronation for 3 weeks.

Postoperative X-rays (AP and lateral) are taken with the cast on.

Postoperative monitoring is essential. It is focused on detection of compartment syndrome (one case in our series), and sensitiveness in the radial territory, particularly the dorsal aspect of the thumb and the first web space.

Pain killers and NSAIDs are prescribed for a few days.

The child is allowed to get out of bed on Day 1 and should wear a protective sling during the whole immobilization period.

15.2.13 Resumption of Activities

The child is usually discharged from hospital 1–2 days after surgery and is encouraged to return to school as soon as he/she is back home. He/she should be excused from sports and physical education for 2 months. At the third postoperative week, the child returns to hospital for removal of cast and X-ray control.

Self-rehabilitation is the rule for the next 4–6 weeks, that is, until the next follow-up visit. During this second visit, range of motion is evaluated, and the surgeon decides whether self-rehabilitation should be continued or rehabilitation should be performed by a physical therapist, knowing that massages and forceful passive ROM are proscribed as they may lead to the development of periarticular ossification.

15.2.14 Implant Removal

The nail is always removed. Although there is no "ideal" time to remove the implant, it is advisable to wait until full range of motion has been recovered. Better not run the risk of reoperating during the rehabilitation period (whether it is self-rehabilitation or rehabilitation performed by a physiotherapist). The appropriate time is around the second or third postoperative month.

Implant removal is usually performed on a day-patient basis using the initial approach. Extra caution is required during dissection of subcutaneous tissue as the presence of surgical adhesions may make it difficult to identify the sensory branch of the radial nerve. Therefore, we think it preferable to use a tourniquet.

Return to sports is allowed as soon as skin healing is complete.

15.2.15 Postoperative Follow-up

Periodical clinical and radiological follow-up for 2 to 3 years is mandatory as growth disturbances are not uncommon, and elbow function may deteriorate even after several years.

However, if after 2–3 years follow-up the morphology of the child's elbow is normal with full range of motion, longer follow-up is unnecessary.

15.3 Complications

15.3.1 Local and Regional Complications

Local and regional complications, whether preoperative or postoperative, are those of any other bone fracture.

However, radial neck fractures are seldom associated with preoperative complications. Protrusion of the fractured end of the bone is most often seen in associated fractures of the radial neck and olecranon, and vascular lesions are hardly ever seen. But, injury to the radial nerve should be systematically sought because of its close location, whether it be at presentation or during reduction, particularly when a punch is used.

Early postoperative complications are those of any surgically treated fracture, including: compartment syndrome, early infection, secondary displacement [11].

15.3.2 Complications Associated with Radial Neck Fractures

A close correlation has been noted between the amount of initial displacement, treatment method, and quality of the functional and radiographic outcome. Open reduction of the radial head often leads to poor results and should be avoided, except in the rare cases of posterior dislocation. The best results are obtained with closed manipulation, but only mildly displaced fractures are amenable to nonoperative treatment. Intramedullary nailing yields similar results to nonoperative treatment; the only factors that may adversely affect the outcome are the amount of initial displacement and the presence of associated bone lesions. Most of these complications result in joint stiffness (more or less severe), most often in pronation-supination, rarely in flexion-extension.

15.3.2.1 Growth Disturbances

Hypertrophic radial head is a frequent complication (involving between 20 and 40% of the cases). We have personally had two cases in a series of 95 fractures managed with FIN. It is due to the hypervascularization, which follows injury. Its clinical impact varies according to the degree of hypertrophy, ranging from normal function to moderate restriction of pronation-supination. There is no appropriate solution to this problem.

Conversely, epiphysiodesis of the proximal radial physis may occur. We have had two cases in our own series. Causes are numerous and include: epiphyseal separation (rare), aggressive reduction maneuvers, repeated nail insertions, multiple perforations with the punch. However, it does not significantly affect function as the resulting shortening is very limited,which is attributed to two reasons: the first one is that the proximal radial physis contributes only 20% of the total growth of the radius, and the second one is the mean advanced age of the involved children.

15.3.2.2 Malunion

Malunion may result either from secondary displacement, or from a large postreduction fracture gap that was not filled during the bone remodeling process. Malunion is more frequently seen after manipulative reduction, but it may also occur after intramedullary nailing if the limb has not been immobilized after the procedure. Malunion produces a cam effect, which restricts ROM mainly in pronation-supination, and which is responsible for cubitus varus deformity. The potential for bone remodeling depends on the child's age. It is generally held that where residual tilt is greater than 30° there is incomplete bone remodeling [3]. Treatment will vary according to the degree of discomfort.

15.3.2.3 Anarchic Ossifications

Intra- or periarticular ossifications may develop and even create a radioulnar synostosis. In most cases, the cause is related to the surgical approach, but it may also be an ossification of the periosteal flap, particularly where there are associated bone lesions, as is the case in high-energy fractures. The three cases that we have had were radial neck fractures with an associated bone lesion (elbow dislocation in two cases, olecranon fracture in one) (Case 2). The degree of functional impairment they may cause depends on their volume and location. Resection may be necessary if ROM is severely restricted, which will require an appropriate postoperative rehabilitation protocol.

15.3.2.4 Necrosis of the Epiphysis

Fortunately, extensive epiphyseal necrosis is a rare occurrence. It is related either to an extended approach or to dislocation of the radial head (Case 3), particularly posterior dislocation (four cases (4.5%) of complete necrosis in our series). It should be pointed out that it is almost systematically associated with a poor functional outcome. Actually, there are many types of partial necrosis, but their rate is likely underestimated as revascularization takes place during the remodeling process so that necrosis goes undetected. These types of necrosis hardly affect function.

15.3.2.5 Nonunion of the Radial Neck

Nonunion of the radial neck also is a rarely reported complication [12]. Still, we have had three in our series of 95 FIN cases (Case 4). Its mechanism is very similar to that of necrosis. A major factor is precarious vascularization, which can be compromised in severely displaced fractures, posterior dislocation and open reduction. At issue is the question of whether this condition should be treated or not as it is generally well tolerated.

15.3.3 Complications Associated with this Technique

15.3.3.1 Vascular Complications

Although we have not personally experienced any vascular complications so far, they cannot be ignored. The most critical step is the creation of the distal hole as anterior misdirection of the awl can place the radial artery at risk. It is recommended to firmly hold the radius in mid-pronation with the thumb and index finger, and direct the awl slightly posteriorly.

15.3.3.2 Implant-related Problems

Implant-related problems are a common subject of complaint. Only in rare instances does it require surgical revision as hardware removal is normally a straightforward procedure.

However, the nail may occasionally irritate the sensory branch of the radial nerve and even extensor pollicis tendons. At worst, skin erosion may occur and should be treated as soon as possible to avoid the potential risk of sepsis. This is why we wish to insist on the importance of a slightly anterior approach and careful trimming of the nail at the end of the procedure. Both will reduce the risk of irritation of the nearby tendons and nerves and skin irritation at the entry point (which is often increased by muscle wasting).

15.4 Indications

Among all the treatment options that are currently available for radial neck fractures, intramedullary nailing is the “gold standard,” whether alone or in association with punching. The reason is that reduction is performed by closed means and preserves vascularization of the radial head, which is known to be a strong predictor of good prognosis [13].

Nonoperative treatment is indicated in Type I fractures, which can be successfully managed with immobilization without reduction (long-arm cast with the forearm slightly pronated for 3–4 weeks). It is also indicated in Type II fractures after manipulative reduction, if adequate stability is achieved.

But, in cases where reduction is insufficient or unstable and in Type III fractures, intramedullary nailing is the treatment of choice as it provides both reduction and stabilization of the fracture. However, immobilization in a plaster cast for 3 weeks is highly recommended for protection purposes (Case 5).

In Type IV fractures, reduction can be achieved with FIN and reduction maneuvers (as described above), alone or in association with punching, or else using an open technique which, however, should be avoided as much as possible. Stabilization is provided by an intramedullary nail and cast immobilization. There are no indications for radiocapitular pin fixation.

Any associated bone lesions should be treated in the same procedure and are not a contraindication to FIN (Case 2).

15.5 Contraindications and Limitations

In cases of radial head dislocation, particularly posterior dislocation, no manipulative reduction should be attempted to avoid the risk of rotating the epiphyseal fragment 180°, which would result in necrosis. Direct nailing is also contraindicated. Open reduction is required, and an intramedullary nail provides stabilization. Some will advocate suturing of the peripheral periosteal structures.

15.6 Case Reports

15.6.1 Case 1

An 8-year-old child fell on her elbow. Initial X-rays, and more particularly the lateral view, showed a Jeffery Type II radial head fracture (a, b). It was treated by closed reduction and FIN. On the fluoroscopic image, note the 180° rotation of the radial head (c). Open surgery was necessary to perform reduction and FIN (again) using a 1.5 mm nail (d, e). The implant was removed during the fourth postoperative month. At 10-month follow-up, function was excellent with full range of motion, but the X-ray showed significant remodeling of the radial head (f). Still, viability of the epiphysis was confirmed by MRI (Fig. 15.9).

Note: this unusual fracture needs to be known better.

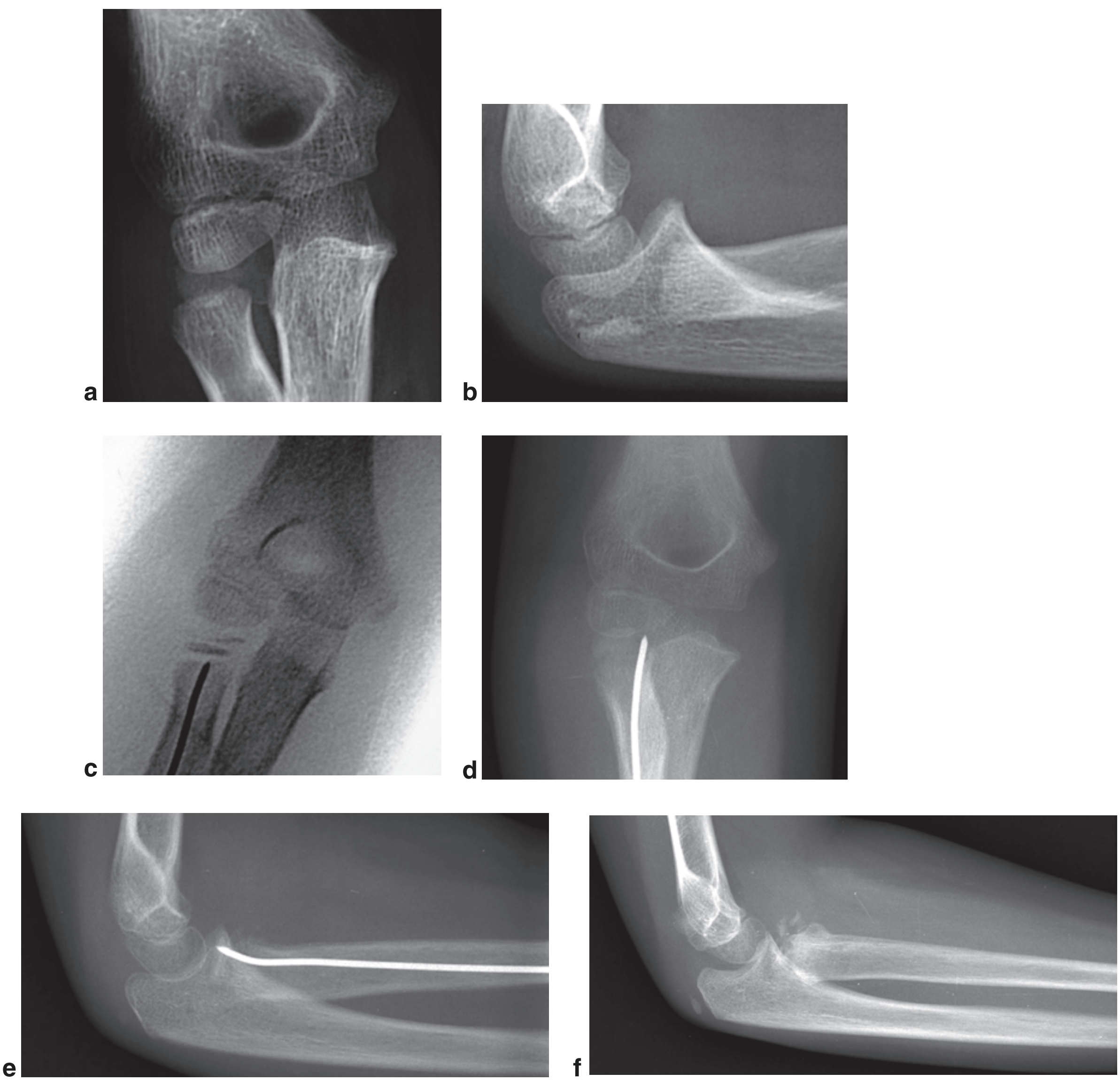


Fig. 15.9 Case 1

15.6.2 Case 2

An 11-year-old child presented with a Type IV radial neck fracture associated with an olecranon fracture (a, b). Treatment consisted in reduction of the radial head fracture with a punch and FIN using a 2 mm nail, and open reduction and fixation of the olecranon fracture with K-wires. At 45 days posttreatment, range of motion had not yet been restored: there was a flexion and extension lag, and a loss of pronation-supination of about 40° in each range (c, d). The implant was removed, but at 1-year follow-up, no improvement was noted. CT showed small calcifications, particularly along the medial border of the radial head that might explain this loss of motion (e). Eighteen months after the initial treatment, arthrolysis was performed and calcifications removed, and an intensive rehabilitation program was initiated. At the 3-year follow-up, the X-ray showed remodeling of the radial head and medial epicondylar groove. There was a loss of 5° both in flexion and extension as compared to the contralateral side, full supination, and a loss of 30° in pronation (as compared to the contralateral elbow) (f, g) (Fig. 15.10).

Note: the severity of this case is attributable to the associated lesions.

Fig. 15.10 Case 2

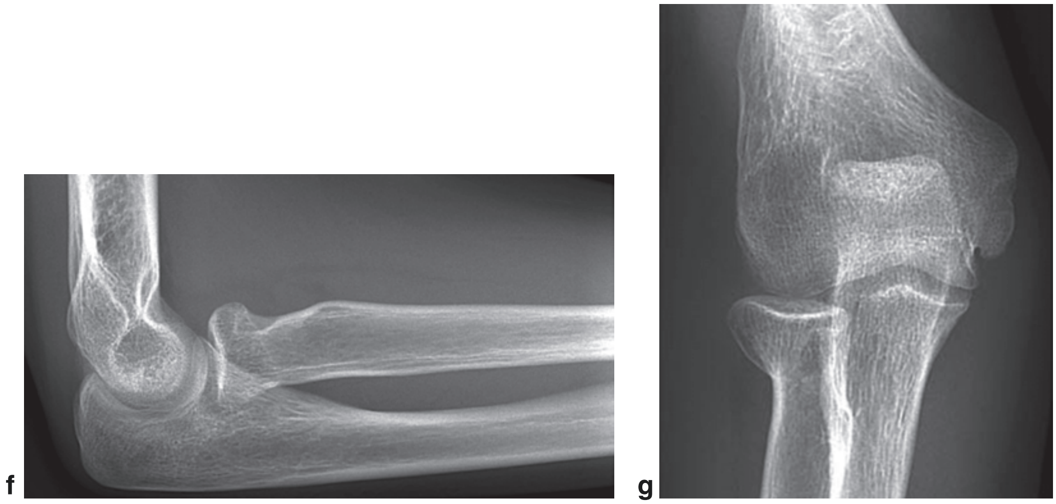


Fig. 15.10 (*cont.*) Case 2

15.6.3 Case 3

An 11-year-old girl was treated for a Type IV fracture of the radial head associated with dislocation of the elbow joint. Dislocation was reduced by closed means (a, b) and radial head fracture by manipulation, prior to performing FIN with a 2 mm nail (c, d). At 3 months, the radiographic result was quite good (e, f). However, necrosis of the radial head gradually developed, leading to a poor functional outcome. Extension lag was 25° but the child had recovered full flexion. Loss of pronation-supination was about 60° in each range (g, h) (Fig. 15.11).

Note: necrosis of the radial head may occur when nonoperative treatment is used.

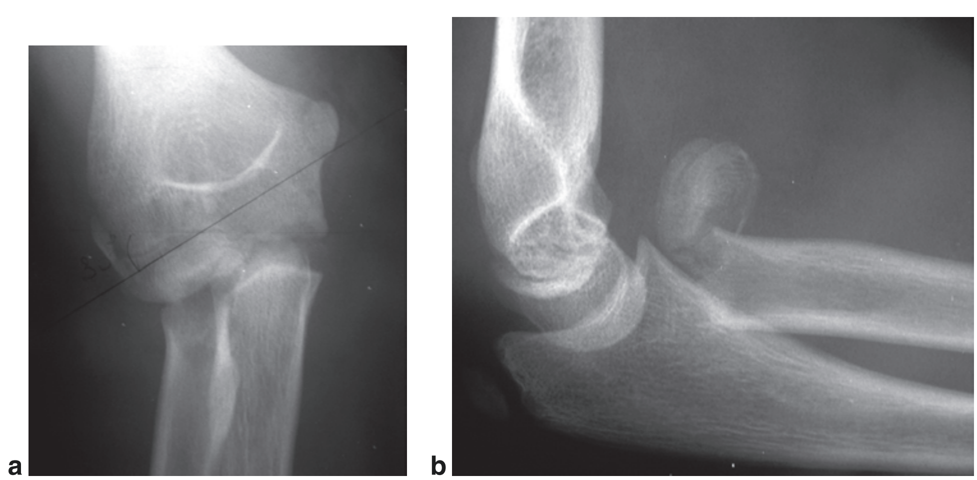
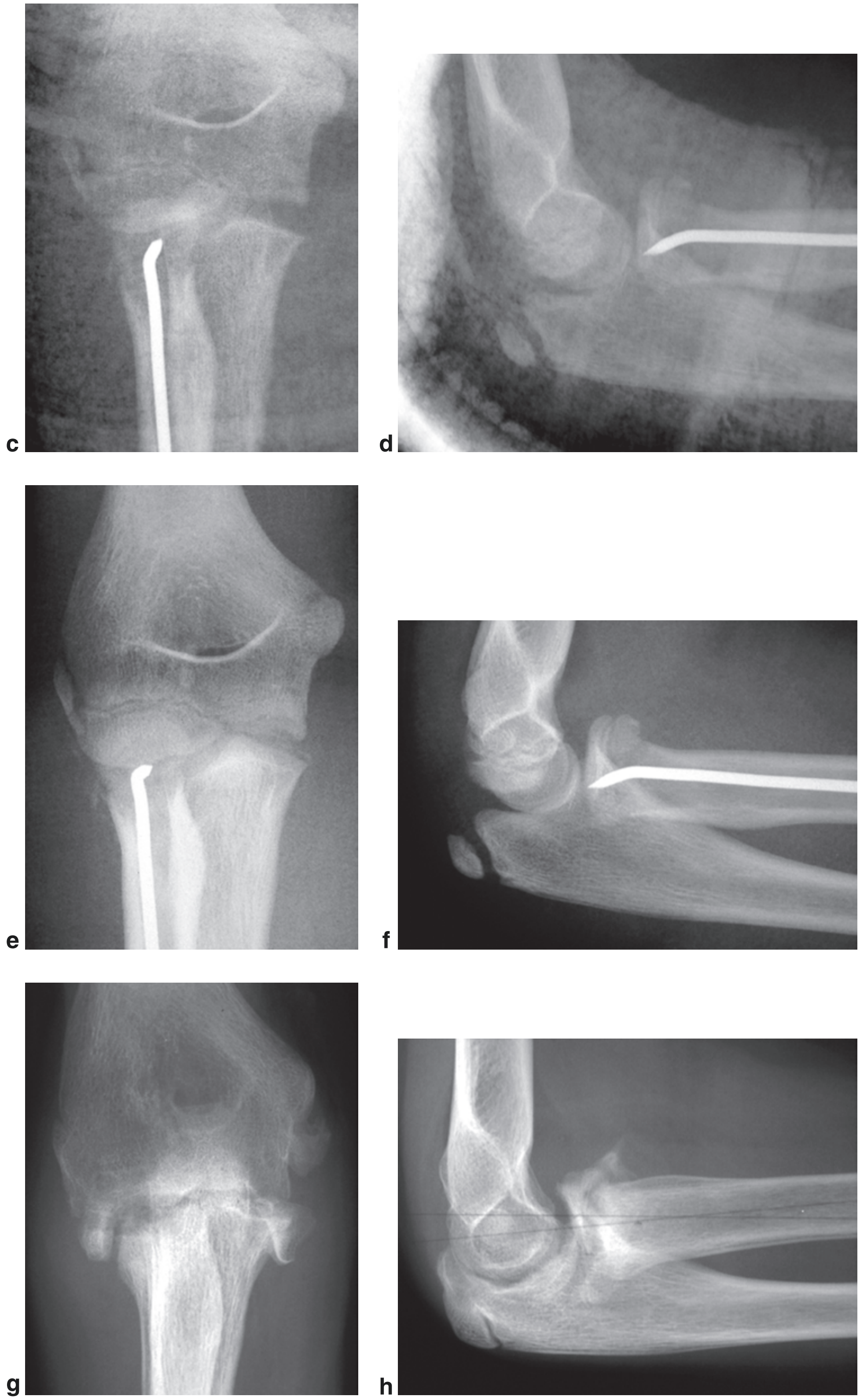


Fig. 15.11 Case 3

Fig. 15.11 (*cont.*)
Case 3



15.6.4 Case 4

An 11-year-old boy operated on for a Type IV fracture. Treatment consisted in punching and FIN using a 2 mm nail (c, d), followed by immobilization in a splint for 3 weeks. Healing was delayed and at the 6-month follow-up, the X-ray showed nonunion of the radial neck (e, f). MRI not only confirmed the presence of fibrous nonunion but also good viability of the radial head (g). As the child complained of functional discomfort, surgical revision was performed 1 year after the initial injury: all fibrous tissue was removed and iliac crest graft was used. Six months later, bone union seemed to be achieved. Function was satisfactory, with a mild residual flexion contracture of 10° and a loss of supination of 40°: flexion- extension = 130°-10°-0°, pronation-supination = 90°-0°-40° (h) (Fig. 15.12).

Note: the intra-articular position of the radial neck may promote nonunion.

Fig. 15.12 Case 4

Fig. 15.12 (*cont.*) Case 4

15.6.5 Case 5

An 8-year-old child with a radial head fracture initially treated by closed means. The control X-ray taken with the cast on showed secondary displacement with tilt greater than 30° (a, b), which was confirmed by CT reconstructions (c, d). FIN was performed using a 1.8 mm tapered nail, with a good radiographic and functional outcome at 3 months postoperatively (e, f). The child had recovered full range of motion (ROM was equal in both elbows) (g, h) (Fig. 15.13).

Note: in children, residual tilt (if any) of the radial head should not exceed 20°.

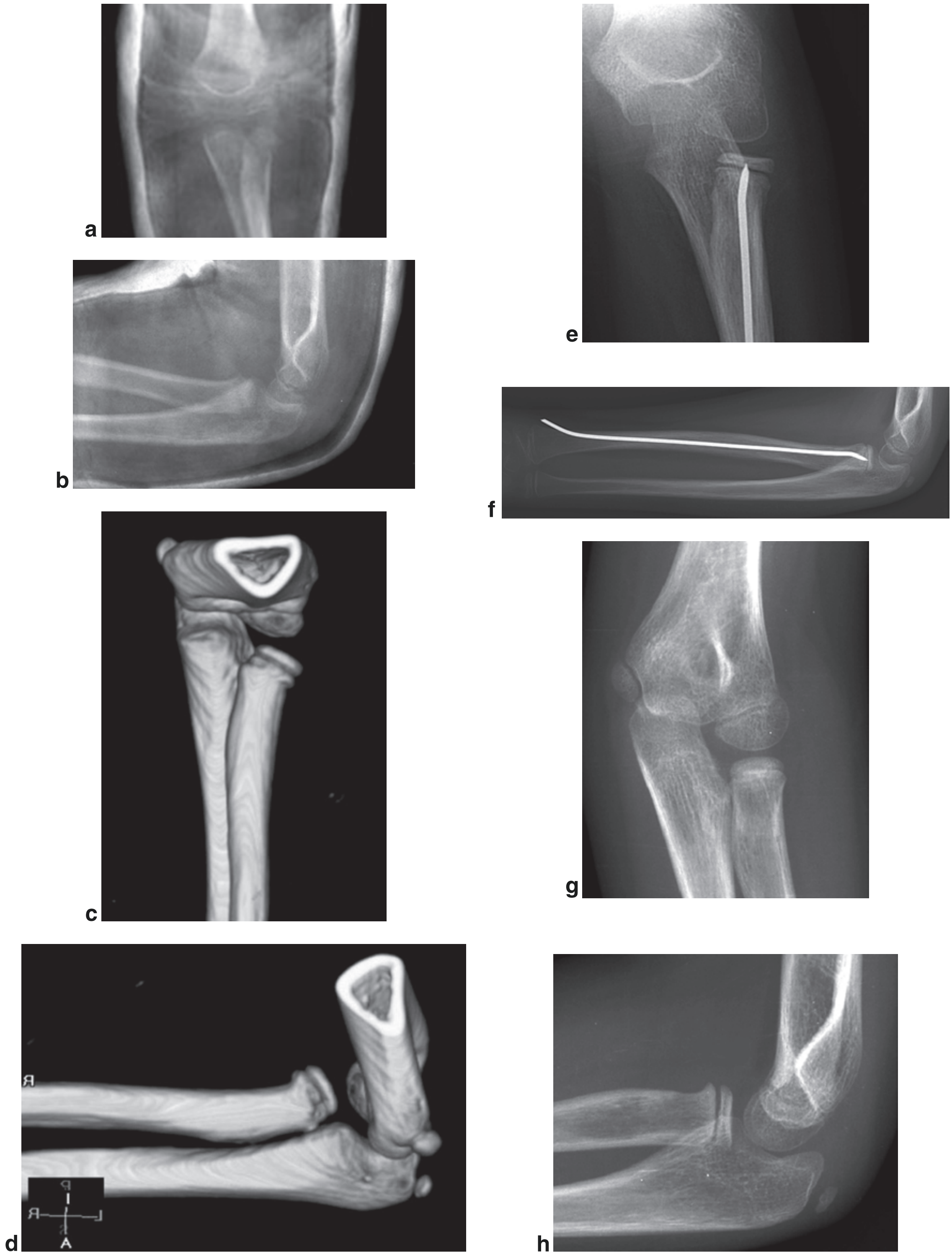


Fig. 15.13 Case 5

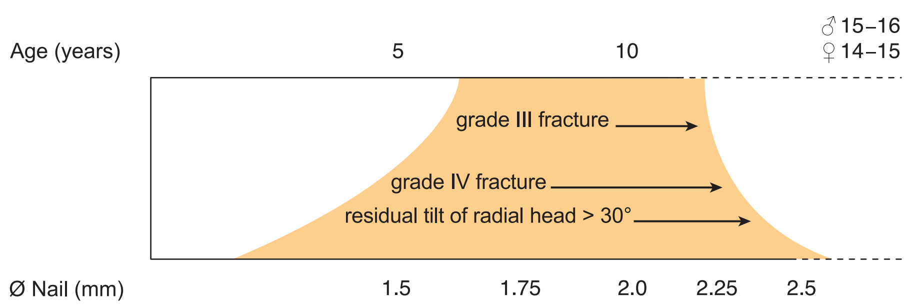
15.7 FIN and Radial Neck Fracture: Postoperative Management in the Absence of Complications

Day 0	• Long-arm plaster cast • AP and lateral radiographs • Continuous monitoring • Operated arm is elevated • Pain killers ± antiinflammatories
Day 2	• Discharge with instructions • Early return to school
Three weeks postop.	• Cast removed; AP and lateral radiographs. • Self-rehabilitation
Two months postop.	• Clinical and radiological (AP and lateral) follow-up • Nail removal is considered • Return to sports
Twelve to twenty-four months postop.	• Clinical and radiological (AP and lateral) follow-up

15.8 Six Key Points

- Whenever possible, reduction should be achieved by closed means, using a punch if necessary.
- A 1.5–2.5 mm nail with a tapered end (for dense epiphyseal bone) is advanced up to the proximal metaphysis.
- Image intensification (AP and lateral views) should be used to make sure that the tip of the nail is positioned right in front of the epiphysis.
- The nail should be impacted into the epiphysis using a slotted hammer (one single try).
- Fracture must be reduced by gentle rotation of the nail combined with appropriate maneuvers.
- Immobilization in a long-arm plaster cast for 3 weeks.

15.9 FIN Indications: Radial Neck Fracture



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Both-Bone Forearm Fracture

16

Pierre Lascombes and Thierry Haumont

16.1 General

16.1.1 Epidemiology

Both-bone forearm fractures account for 5% of all fractures in children and usually occur at a mean age of 8.5 years (9 years for boys, 7.5 years for girls). The sex ratio is M 2.5:F 1.

16.1.2 Mechanisms of Injury and Classifications

Most often, a both-bone forearm fracture is an indirect injury resulting from a fall on an outstretched hand, with the forearm supinated. Direct violence is a less frequent cause. The Monteggia fracture/dislocation is an ulnar fracture with associated proximal dislocation of the radial head, which is typically caused by a direct blow to the ulna. More than one in two fractures are the result of a simple fall from a height. One-third of these fractures occur during sports activities: judo (16.9%), gymnastics (7.3%).

Both bones are involved in the vast majority of cases (85.7%), radius only: in 6.5%, ulna only: in 2.5%. The Monteggia fracture/dislocation rate is 4.7% and the Galeazzi fracture rate is 0.6%.

Both-bone fracture patterns:

- Transverse: 64%.
- Oblique: 14.4%.
- Spiral or comminuted fractures are rare.

Anatomic location:

- Middle third (both bones): 65% in the radius and 70% in the ulna.
- Distal third: 20%.
- Proximal third: 13 and 9% in the radius and the ulna, respectively.

Displacement of bone fragments (both bones):

- Thirty percent in greenstick fractures.
- Thirty percent in displaced fractures, with some contact between the fragments.
- Twelve percent in displaced fractures, with overlap of the fragment ends.
- Three to four percent in plastic bowing fractures: these are often very subtle on plain films; and may be misdiagnosed for Monteggia fractures, if unknown.
- Other types are combinations of different displacements.

Skin wounds have been reported in 7.5% of Gustilo Type I fractures, seldom in Type II and III. Vascular complications are rare, whereas initial nerve lesions are seen in 3.4% of patients. However, they have a very good prognosis.

16.2 Combined Antegrade/Retrograde FIN (Retrograde for Radius, Antegrade for Ulna) in Middle Third and Proximal-Third Fractures [1, 2]

16.2.1 Anesthesia

General anesthesia should always be preferred [3–5].

16.2.2 Patient Positioning

The child is positioned supine on the operating table with the injured upper limb placed on an arm table.

P. Lascombes, *Flexible Intramedullary Nailing in Children*,
DOI: 10.1007/978-3-642-03031-4_16,

The surgeon stands close to the forearm, which is extended and supinated. The assistant stands either in front of the surgeon or at the end of the arm table (out of the way of the C-arm) (Fig. 16.1).

16.2.3 Image Intensifier

The image intensifier is placed parallel to the patient's body. It is positioned directly vertical for the AP view. For the lateral view, one can either rotate the C-arm, or internally rotate the patient's whole upper limb, to avoid displacement of the fracture.

16.2.4 Closed Reduction

If flexible intramedullary nailing (FIN) has been selected right away, an attempt at closed reduction is useless, since redisplacement during draping is almost inevitable. But in many instances, FIN is decided after failure of closed reduction. The prospective study presented at the SOFCOT Meeting [6] suggests that, after approximately 10 min of failed attempts, it is advisable to convert to FIN.

Fig. 16.1 Patient's *upper limb* is placed on an arm table. Image intensifier is used

16.2.5 Operative Field

A tourniquet is placed at the upper arm just in case open reduction would be necessary. The entire upper limb is sterile prepped and a sterile upper extremity drape is placed.

16.2.6 Selection and Preparation of the Implants

Follow the rule of thumb for nail diameter choice: nail diameter = 40% of IM canal diameter. In some circumstances, the nail diameter may reach 50% of the IM canal. There will be one nail for each bone.

Therefore, depending on bone size, the average nail diameter is:

- 1.5–1.75 mm for a child aged 6–9 years
- 2–2.25 mm for a child aged 9–12 years
- 2.5 mm for a child more than 12 years old

Most often, radial and ulnar nails are identical. However, depending of the child's anatomy, a smaller diameter ulnar nail than radial nail can be used (e.g., a 2.0 mm diameter ulnar nail and a 2.25 mm radial nail).

Stainless Steel is the preferred material in forearm fracture nailing. The elastic properties of Titanium in smaller diameters can hinder insertion and fracture crossing, especially in the case of refractures, where intramedullary callous has further narrowed the isthmus.

The tapered tip of the nail protects against cortical bone penetration and catching on the walls of the canal during advancement. The nail tip is slightly curved (30–40°) over a length of 3–4 mm at its leading end, to smoothly "take the turn" at the metaphyseal/diaphyseal junction. As the length of the curve must be smaller than the diameter of the medullary canal, it is sometimes necessary to slightly shorten the curve of certain manufactured nails. In case of in situ bending, care should be taken to bend the tip in the same plane and direction as the contouring, to ensure proper orientation of the nail.

Then, both nails are gently contoured to achieve a curvature of 40–50°. The apex of the curve should be located at the level of the fracture site at the end of the procedure.

Bending and contouring are effective in assisting fracture reduction where incomplete: rotating the nail allows engagement of the opposite fragment. Then, the displaced fragment is automatically pulled back and realigned, as the nail is pushed across the fracture site with the help of a slotted hammer.

16.2.7 Radius First or Ulna First?

There is a saying "first reduced > first nailed"; and it is very sensible, indeed. This way, there is no risk of reduction being lost while you are trying to reduce the second bone. In 80% of the cases, the radial fracture is managed first; because the radius lies in a depression, which may make reduction more difficult to perform after the ulna has been nailed.

Once the radius is done, reduction of the ulna is quite easy, as its posteromedial border can be palpated beneath the skin. Should ulnar reduction prove to be a little tricky, here is a useful tip: just allow 10–20 mm of the radial nail to engage the opposite bone fragment past the fracture site. As a matter of fact, increasing motion at the radial fracture site will facilitate reduction of the ulnar fracture.

In only 20% of the cases is the ulna managed first: the ulnar fracture is less displaced, or the surgeon finds it easier to do it this way.

16.2.8 Retrograde FIN for Radius

The initial steps of the retrograde FIN technique used for the radius are identical to that for management of a radial neck fracture. The entry hole for the nail is made on the lateral aspect of the distal metaphysis, 10–20 mm above the distal physis (which is preserved), that is, 30 mm above the tip of the radial styloid, preferably on the volar subcutaneous border of the distal radius. To be more accurate, it is located between the insertion of the brachioradialis tendon (long supinator), dorsally, and the ventral surface of the radius where the radial artery lies. This avoids potential damage to the radial vein or the sensory branches of the radial nerve during dissection. The nail does not pass between the extensor tendons. The awl is directed dorsally, to reduce the risk of the awl slipping anteriorly and, thus, to avoid injury to the radial artery (Fig. 16.2).

Therefore, a 20 mm longitudinal skin incision is made anterior to the intermediate antebrachial vein so that its proximal end is right over the planned entry hole. Since the nail is inserted obliquely, more room is needed distally to avoid skin impingement.

For the first procedures, the surgeon may feel more confident with the tourniquet inflated, working in a conventional manner. As he/she becomes more familiar with the technique, he/she can operate in a "blind" fashion, using blunt dissection down to the bone surface and avoiding sharp dissection whenever possible.

During this step, the radius must be firmly held in neutral alignment by the surgeon, with the left thumb and index finger (if right-handed). Thus, the incision can be opened without bleeding, and the right hand works while the left hand is immobile.

The 3 mm diameter short awl should be handled as shown in Fig. 16.3; this protects against injury in case of slippage. The awl is inserted perpendicular to the bone surface at the desired level. There is a typical grinding feel, as the awl enters the cancellous bone with the aid of slight rotatory movements (clockwise and counterclockwise). The awl is then directed upwards, to create an oval-shaped hole and to avoid penetration of the far cortex.

The awl is left in situ. The surgeon grasps the radial nail by the attached T-handle – taking care not to move his/her left hand – and positions the nail at the proximal end of the incision, with the curved tip perpendicular to the entry point. As the assistant slowly withdraws the awl, the surgeon inserts the nail into the incision and easily finds the entry hole into the bone. Upon contact with the far cortex, the nail is rotated so that it points toward the mid-portion of the shaft (Fig. 16.4).

The nail is slowly advanced upwards, while axial traction is applied to the patient's hand with the aid of rotatory movements, as previously described. If the angle of curvature of the nail's tip is too small, the nail will be unable to "make the turn" at the metaphyseal-diaphyseal junction. If the nail gets jammed at a higher level, one must fully rotate it to free its tip and to allow the nail to proceed upwards, until it reaches the fracture site. In cases where it is definitely stuck, shortening the curvature of the tip of the nail should solve the problem.

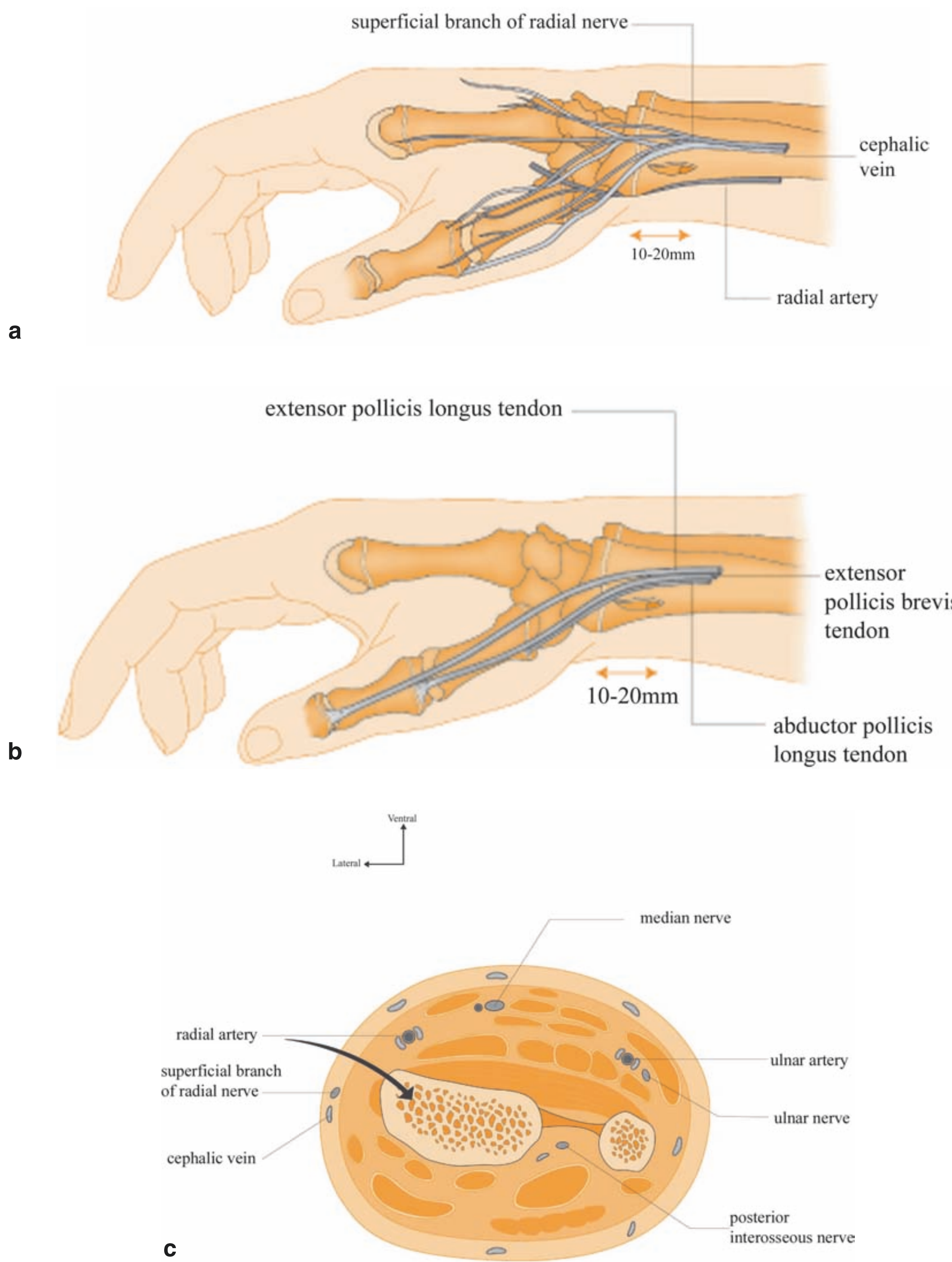


Fig. 16.2 Surgical approach to the radius. A 15–20 mm longitudinal incision is made anterior to the intermediate antebrachial vein and sensory branch of the radial nerve. (**a**) The hole is created in an anterior-posterior direction away from the radial artery; (**b**) Entry point is located 10–15 mm above the physis on the anterolateral aspect of the distal radius, anterior to the brachioradialis, (**c**) Anatomic section of the distal one-fourth of the forearm: anterolateral approach, and anterior to the extensor pollicis tendons

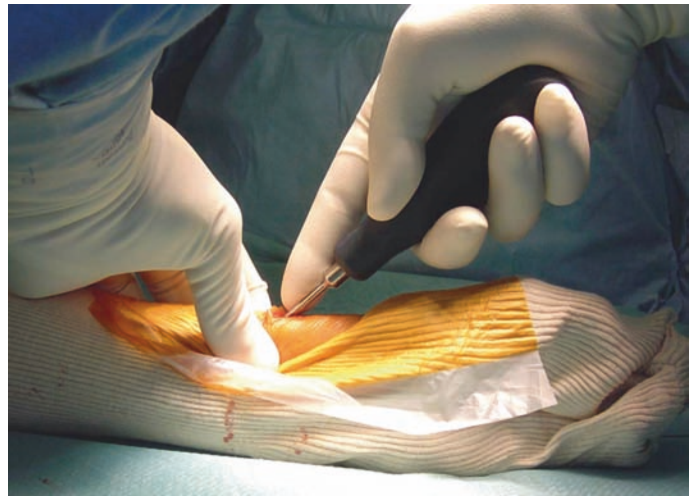


Fig. 16.3 Awl properly positioned

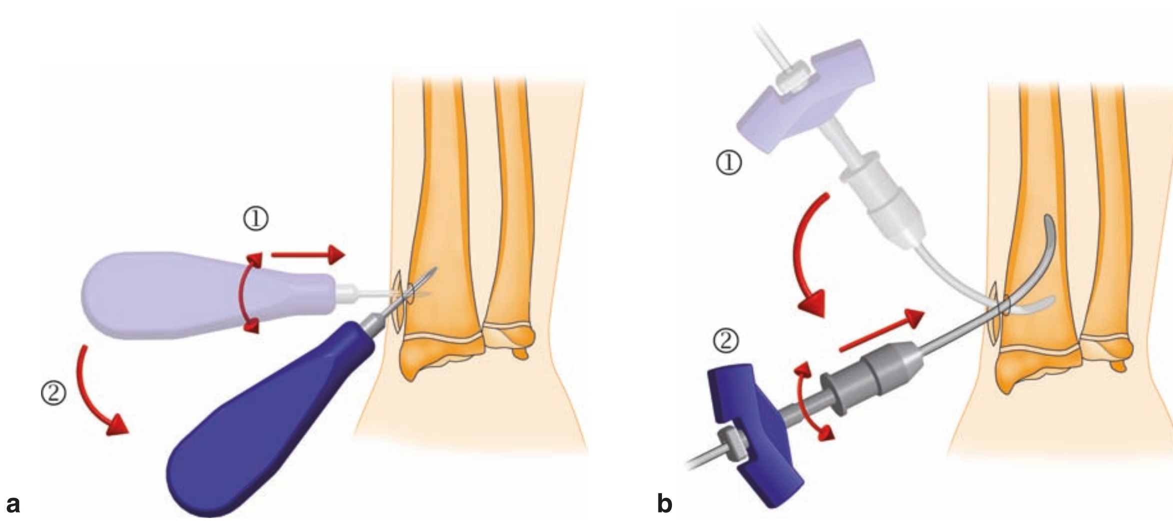


Fig. 16.4 Flexible intramedullary nailing (FIN) technique for radius: (**a**) entry hole is created with the awl; (**b**) nail insertion.

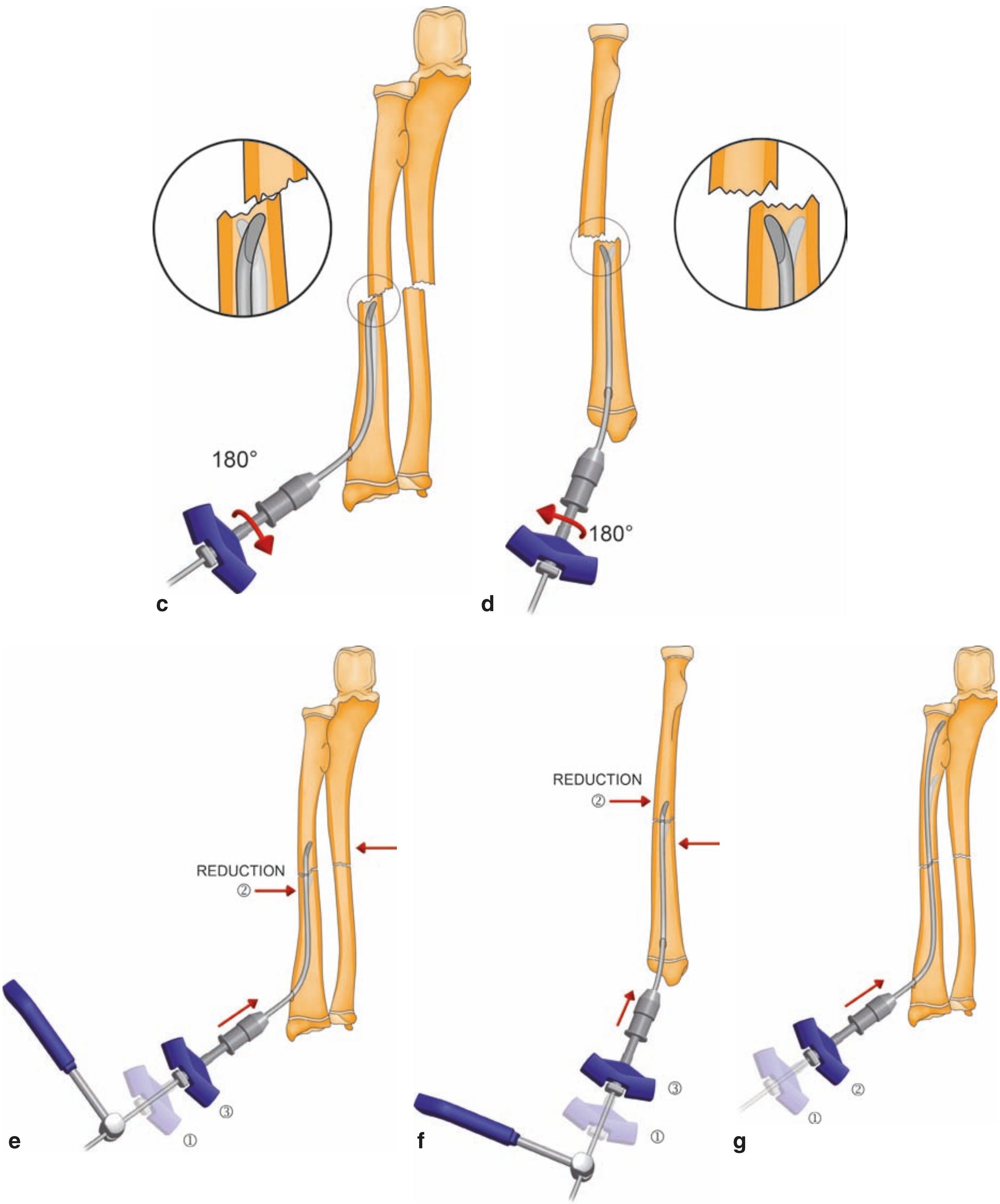


Fig. 16.4 (*cont.*) Nail is advanced up to the fracture site with its tip directed to the proximal bone fragment: AP view (**c**) and lateral view (**d**). reduction and crossing of the fracture site. Nail impacted using a slotted hammer: AP view (**e**) and lateral view (**f**); (**g**) nail is advanced up to the radial neck and then rotated 180° so that its concave side faces the ulna

A first check is performed using fluoroscopy to confirm the correct position of the radial nail and proper orientation of its tip. Then, reduction of the radial fracture can be achieved by performing the usual maneuvers and checked in both the frontal and sagittal planes, with rotation of the patient's whole upper limb, as previously described. It is essential that the nail tip points (AP and lateral) toward the opposite fragment. To achieve this, the T-handle must be rotated in either direction by a maximum of 90°.

Once proper orientation has been achieved, the assistant cautiously advances the nail using light hammer blows and locks the position of the T-handle, while the surgeon maintains reduction. As a matter of fact, if the T-handle rotates as the nail progresses upwards, the nail may be misdirected into the proximal soft tissues. Image intensification (AP and lateral) is most useful to monitor crossing of the fracture site. Once the fracture site has been crossed, the surgeon rapidly feels stabilization.

After this critical step, the nail is advanced further, with its concave side facing the ulna (in order to restore the radial bow), until its tip reaches the radial neck.

16.2.9 Antegrade FIN for Ulna

The entry point for the ulnar nail is located on the posterolateral aspect of the olecranon. Therefore, the nail end that is buried in the anconeus muscle (short extensor) is not stressed when the elbow rests on a table (for instance). The posteromedial approach is risky, because of the anatomic proximity of the ulnar nerve. Insertion of the nail through the top of the olecranon is proscribed because it inevitably results in painful prominence of the nail tip and even protrusion through the skin every time the elbow flexes.

The elbow is flexed and the arm is internally rotated to afford access to the olecranon. A 20 mm longitudinal incision is made 30 mm below the tip of the olecranon on the posterolateral aspect of the bone, so that its distal end is right over the planned entry hole. With oblique insertion of the nail, more room is needed proximally to avoid skin impingement (Fig. 16.5).

Following fasciotomy, blunt dissection is carefully performed down to the bone surface, avoiding sharp separation of muscles whenever possible. During this step, the olecranon must be firmly held by the surgeon, so that the instruments can be properly positioned on the lateral aspect of the ulna.

The entry hole is created using the same method as in the radius. The short awl is easily inserted into the cancellous bone, taking care to avoid slippage toward the medial aspect of the olecranon or the elbow joint. Nail insertion is a straightforward step, as long as one follows the initial path through the soft tissues: The trick is to advance the nail as the awl is slowly withdrawn (the nail replaces the awl) (Fig. 16.6).

Then, the nail is advanced down the ulnar shaft. Due to the small diameter of the ulna, the length of the curved tip should not exceed 3 mm. If it gets jammed, it may need some trimming.

Reduction is performed when the leading portion of the nail has reached the fracture site. A reliable landmark for reduction is the posteromedial border of the ulna, which is easy to palpate. The ulna is much easier to reduce than the radius. This is the reason why it is advisable to do the radius first. As previously mentioned, in case of difficulty to reduce the ulna, one may extract the radial nail to about 10–20 mm proximal to the fracture line. Increased mobility of the radius facilitates reduction of the ulna. The tip of the nail is directed to the distal fragment under fluoroscopic guidance (AP and lateral).

As for the radius, once proper orientation has been achieved, the nail is carefully advanced across the fracture site, using light hammer blows while the surgeon maintains reduction. The assistant should be careful to lock the position of the T-handle in order to push the nail straight ahead. After this critical step, the nail is advanced further (as described above) until it reaches the distal metaphysis. With the curved tip directed laterally, the concave side of the nail faces the radius.

16.2.10 Final Reduction

A perfect construct is achieved when the curved tip of the radial nail points medially and that of the ulnar nail points laterally. This ensures that the nails have opposing concavities and that elastic memory provides stabilization through interosseous membrane tightening. Once final position is achieved, a firm hammer blow is applied to anchor each nail tip into the opposing metaphyseal segment. This minimizes the risk of cutout of tips into Haversian canals.

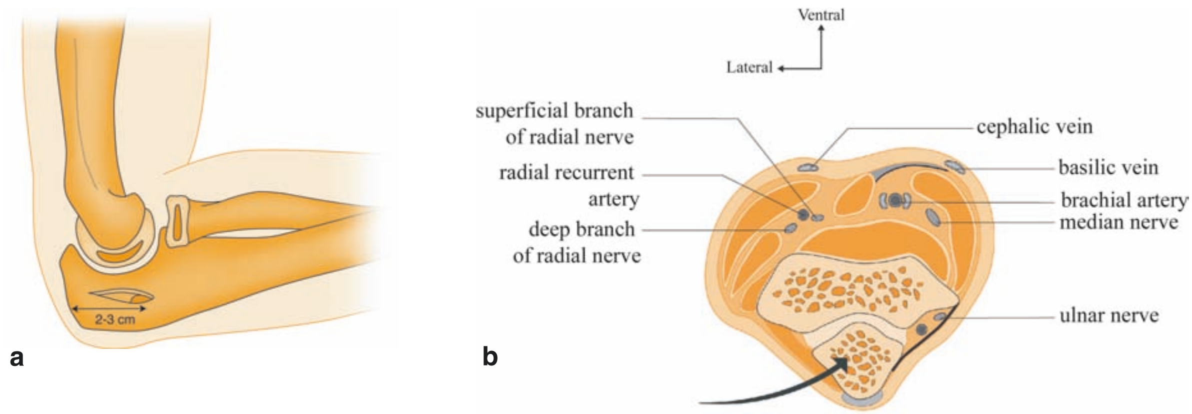


Fig. 16.5 Surgical approach to the ulna: (**a**) entry point is located 20–30 mm distal to the tip of the olecranon on the posterolateral aspect of the bone; (**b**) anatomic section of the elbow

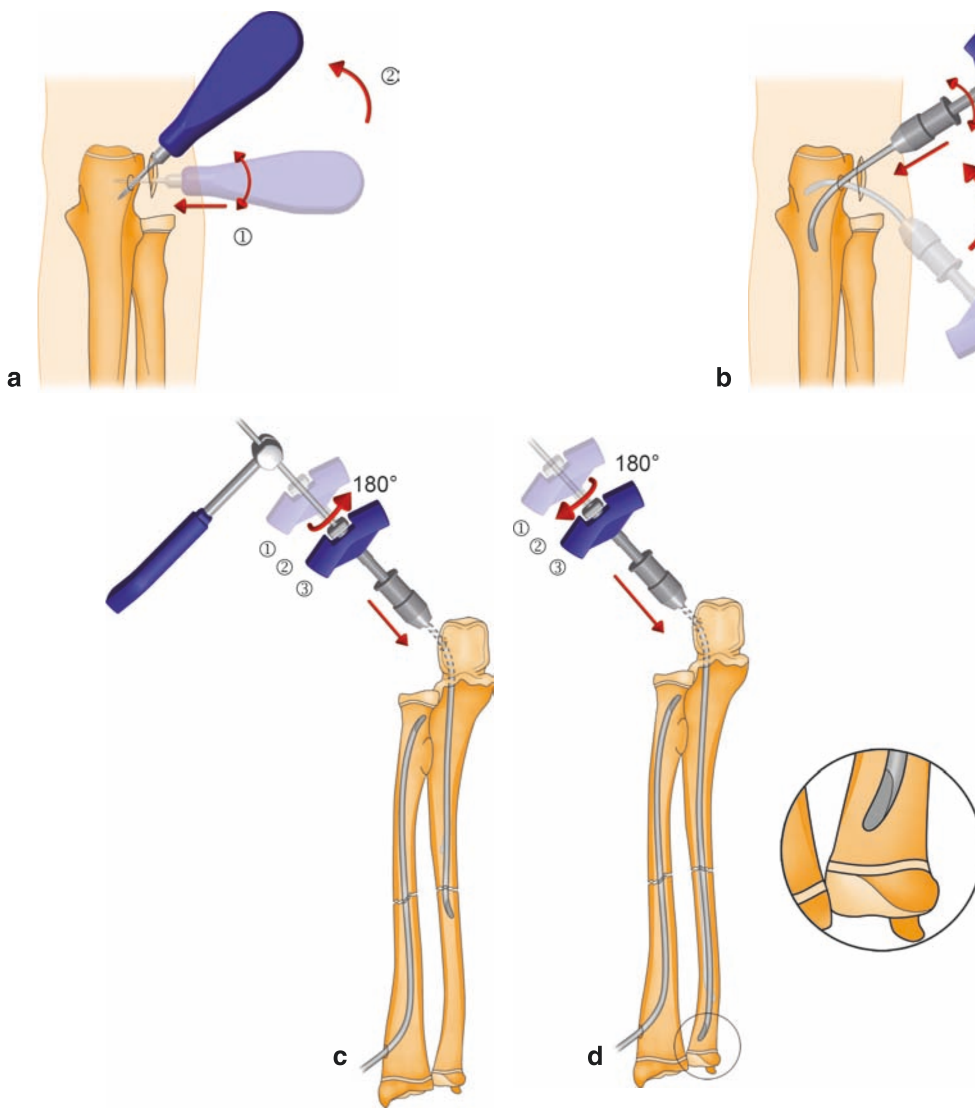


Fig. 16.6 FIN technique for ulna: (**a**) entry hole is created with the awl; (**b**) nail insertion; (**c**) nail is advanced down to the fracture site and pushed with a slotted hammer across the fracture; (**d**) nail is advanced down to the distal metaphysis with its concave side facing the radius

Additionally, it provides a firm anchorage and helps the nails resist axial rotation.

16.2.11 Wound Closure

At the end of the procedure, the trailing ends of the nails are slightly bent to keep them at a distance from the bone, and carefully trimmed using cutting pliers to make a clean cut that will not cause injury to the subcutaneous tissues. Only 3–5 mm should protrude out of the bone to facilitate later removal. In case of excessive protrusion, the use of an impactor may be necessary to recess the nail ends. The wound is closed without drainage and a compression dressing is applied (Fig. 16.7).

One critically important step is to move the forearm through its full range of pronation and supination to confirm adequate reduction of the fracture in the horizontal plane, which is further checked on AP and lateral radiographs (Fig. 16.8).

16.2.12 Types of Both-Bone Forearm Fractures

16.2.12.1 Distal-Third Fractures (J. M. Laville)

The ideal construct is that described above, using combined antegrade/retrograde FIN. However, the radial nail tends to cause fracture displacement (Fig. 16.9). One technical trick is to use a very short nail to maintain reduction (Fig. 16.10). Certain radial fractures in children do not meet the classification criteria for wrist fractures or shaft fractures, and are sometimes improperly called "fractures of the junction of the middle third and distal one-fourth of the radius." Fixation of these fractures, which are often unstable and anteriorly displaced, is a "headache" [7]. If one strictly adheres to FIN principles, one can manage these cases by simply moving the entry point to a posteromedial position: It is the so-called "posteromedial FIN technique for radial fractures" [8].

Technical Considerations

The entry point is located on the posteromedial aspect of the radial metaphysis. The surgeon should carefully

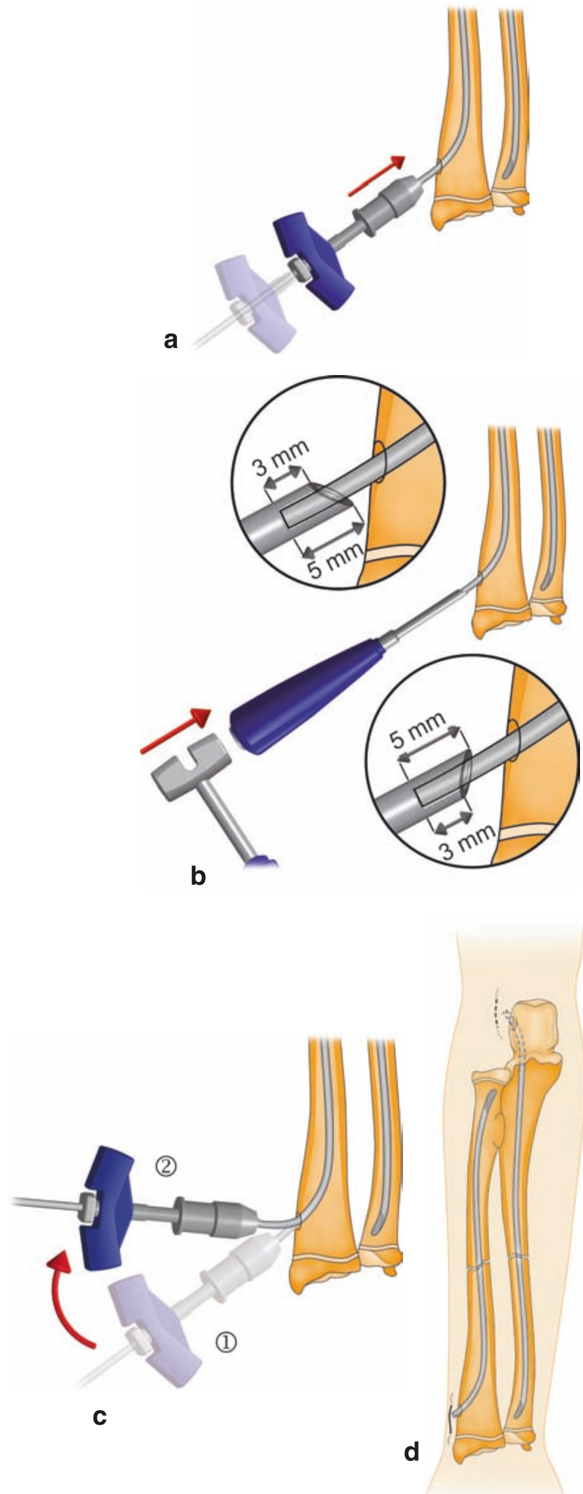


Fig. 16.7 (**a**) Insertion of the nail; (**b**) trimming and impacting the nail; (**c**) bending of the radial nail with the T-handle; (**d**) final positioning

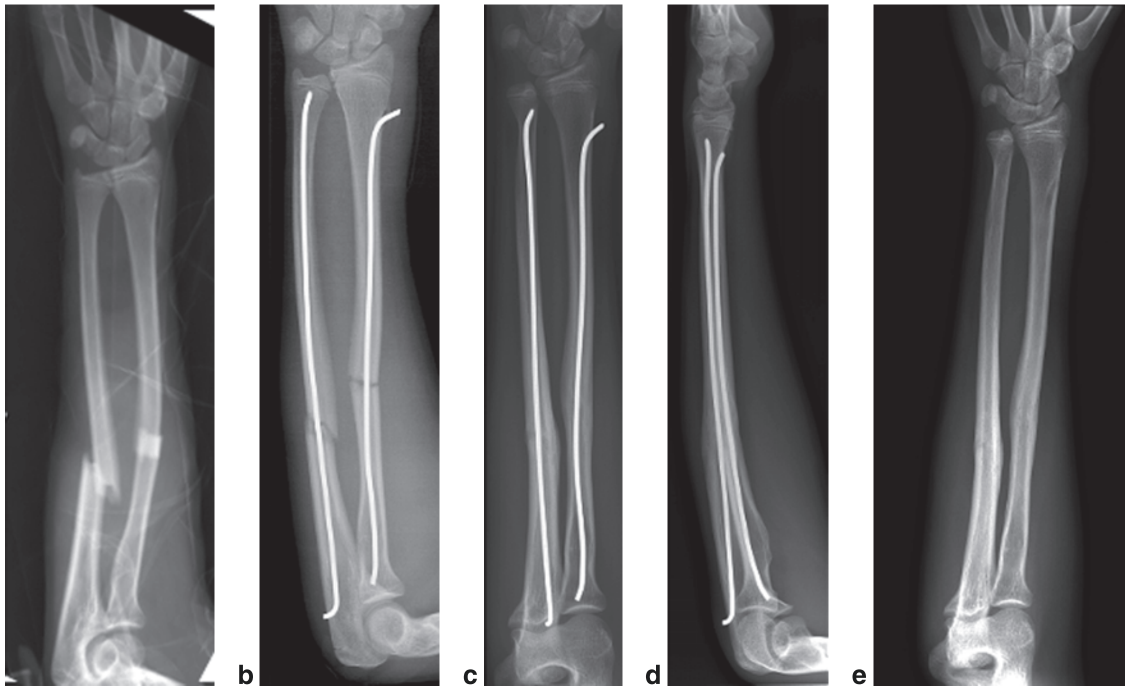


Fig. 16.8 A 10-year-old girl with a complete unstable fracture at the junction of the middle and proximal third of both bones of the forearm (**a**). FIN was performed in both bones, using two 2.2 mm stainless steel nails. Note the perfect orientation of the nails, with the radial nail directed to the ulna and vice versa (**b**). Six months later, anatomic axes have been restored and function is normal. (**c**, **d**) Bone union has been achieved. (**e**) X-ray taken at 8-month follow-up: final result after removal of the nails

preserve the physis (Fig. 16.11). A mini incision is made and blunt dissection is performed using Halsted forceps to preserve tendinous structures. The entry hole is created with the awl directed straight upwards. The nail is contoured and inserted up to the proximal metaphysis without disturbing the physis. The convex side of the curve faces the anterolateral aspect of the bone, which prevents anterolateral displacement of the distal fragment. At the end of the procedure, the trailing end of the nail is trimmed and buried beneath the skin (Fig. 16.12). Immobilization in a windowed, long-arm cast for 5 weeks is recommended.

A fractured ulna is managed using a conventional antegrade technique and a posterolateral approach to the olecranon (as described above). Hardware is generally removed between the fourth and sixth postoperative months.

Discussion

Instability of this type of fracture has been attributed to the pull of three muscles: the brachioradialis, the extensor pollicis longus, and the adductor pollicis [7]. After reduction, if the fracture site is still too unstable to permit immobilization in a long-arm cast with the wrist extended, internal fixation must be considered [5]. Placement of an anterior plate will require an open approach, which may cause injury to the physis; the plate will have to be removed later on, using the same approach. Although antegrade FIN for the radius would sound logical from a mechanical point of view, the approach required makes it very hazardous. Radial nerve palsy has been reported in two cases after using a proximal approach to the radius, which resolved spontaneously [9]. In contrast, posteromedial FIN is a straightforward, time-saving procedure with good cosmetic results. Furthermore, hardware removal is easy. This method is mechanically justified, provided that the fracture is not too distal; since, with a posterior entrance into the distal radius, the nail has sufficient elastic strength to resist anterior displacement. Blunt dissection allows safe retraction of the extensor tendons, which avoids transfixion. As far as we are concerned, we have never experienced tendon injuries. Therefore, in this

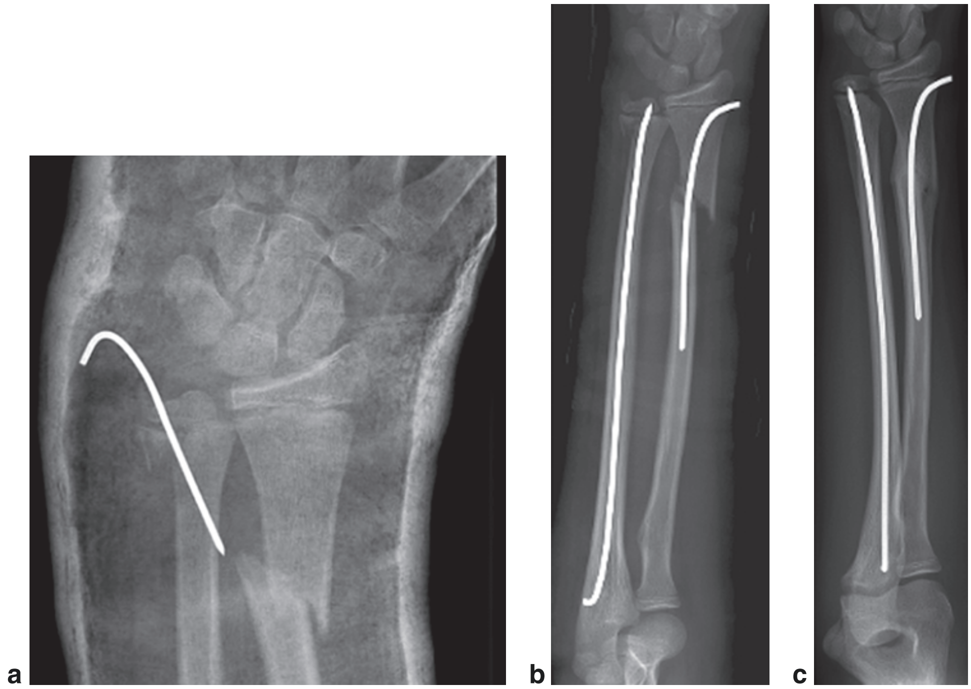


Fig. 16.9 A 10-year-old girl with a fracture of the distal radius associated with a Salter II epiphyseal fracture of the ulna was transferred to our department. The child had been treated with internal fixation and cast immobilization (**a**); (**b**) due to persistent displacement of the fracture, surgical revision was necessary. Both radius and ulna were managed with FIN: note the displacement produced by the radial nail; (**c**) 3 months later, bone union has been achieved and normal function is restored thanks to optimal bone remodeling

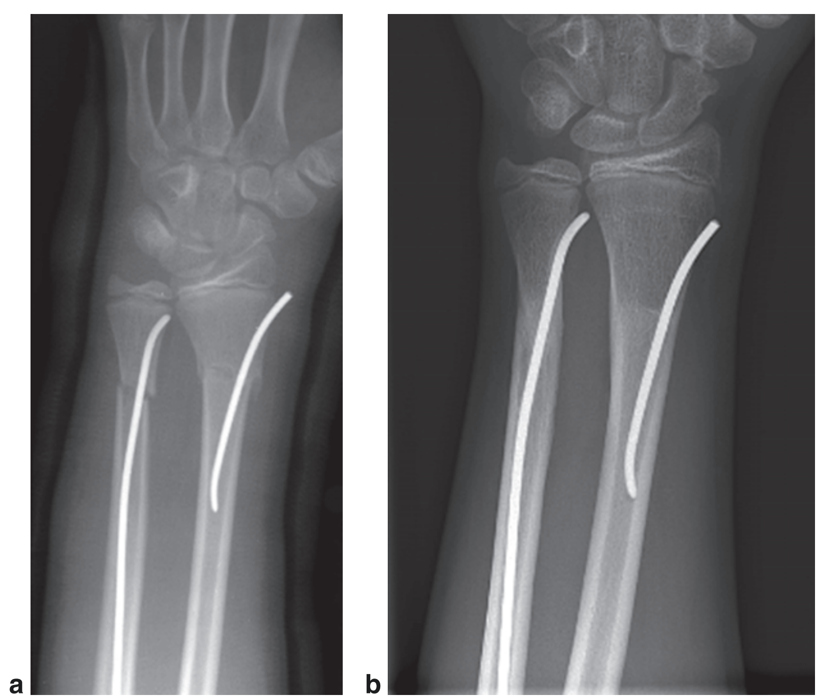


Fig. 16.10 A 15-year-old boy with fracture of the distal one-fourth of both bones of the forearm: construct is unusual with antegrade FIN for the ulna and retrograde FIN for the radius (using a short nail in a lateral position) using 2.5 mm stainless steel nails (**a**); (**b**) 6 months later, bone union has been achieved

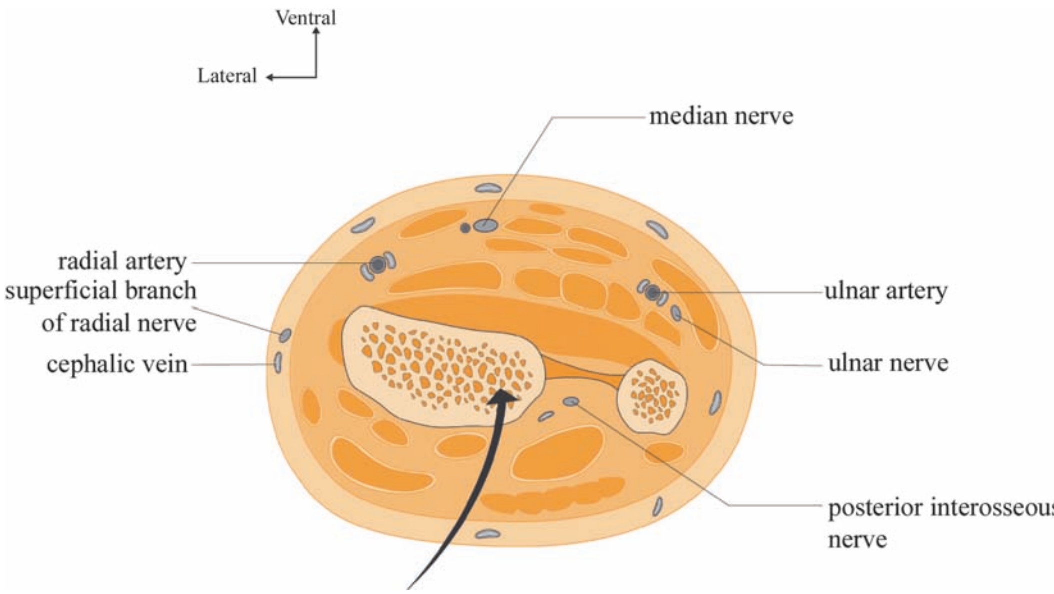


Fig. 16.11 Anatomic section of the distal one-fourth of the forearm: posteromedial approach

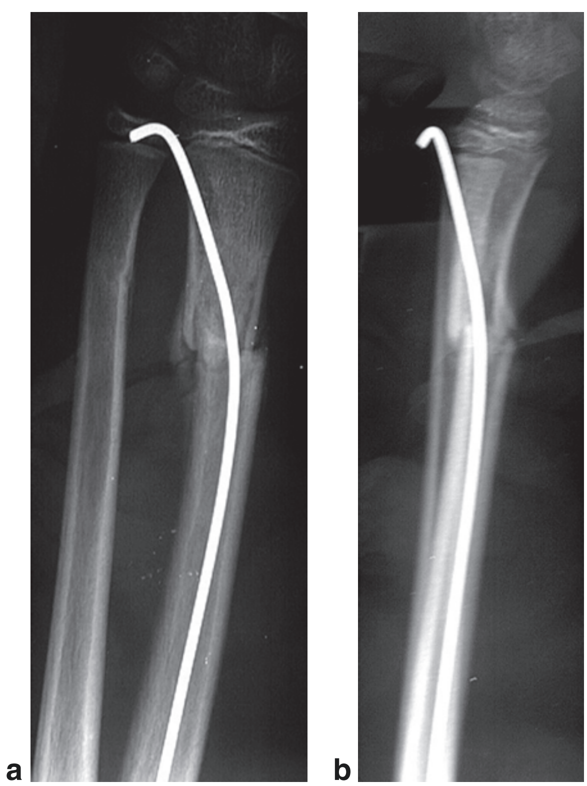


Fig. 16.12 Recurrent fracture at the metaphyseal-diaphyseal junction in an 8-year-old boy. Posteromedial FIN, AP view (**a**) and lateral view (**b**)

situation, posteromedial FIN can safely be used as a primary or secondary treatment.

16.2.12.2 Isolated Fracture of the Radius [10]

Nonoperative treatment is often successful, but an unstable proximal fracture in a young adolescent will require retrograde FIN (Fig. 16.13). In the rare cases of severe displacement of the fracture, open surgery is often inevitable, due to the extreme difficulty to achieve reduction by closed means.

16.2.12.3 Monteggia Fracture-Dislocation [11]

First of all, a dislocation of the radial head must be reduced. Subsequent steps depend on the quality of the ulnar reduction. If the reduced fracture is stable, a successful outcome can be expected with nonoperative treatment. In case of instability, antegrade FIN is suggested for the ulna (as previously described) as an alternative to a plate and screws. Due to the necessity of having an elastic force that prevents dislocation of the radial head at the end of the procedure, it is essential that the concave side of the ulnar nail faces anteriorly. This is evidenced by the anterior position of the curved tip (Fig. 16.14). The upper arm is immobilized in a long-arm plaster cast for 1 month to prevent dislocation of the radial head [6, 7, 11].

16.2.12.4 Recurrent Fractures

Typically, recurrent fractures [12–15] occur between 3 and 18 months after the causative trauma in 6–10% of the cases managed nonoperatively [15]. Contributory factors include residual angulation and nonpatency of the medullary canal, that is, inadequate healing [16, 17]. What happens is that the lamellar bone plug that occludes the canal alters the mechanical behavior of the bone shaft and creates a weakened zone. Slight malunion (if any) will further weaken the bone so that any low-energy trauma will cause the bone to refracture at the same site. Diagnosis is made based on history and on the radiographic appearance of the fracture: The fracture line is "too clear"; and bone enlargement indicates a periosteal response to the injury. A second manipulative reduction is generally badly tolerated, both by the child and the family; because the child will have to be immobilized in a plaster cast for 3 months, and also because the anomalies that promoted recurrence are difficult to correct. Therefore, FIN is an excellent treatment option but technically more challenging than in fresh fractures [15, 18]. The reason is that the medullary canal is occluded so that the nail cannot reach the fracture site or cross it. This is why a direct approach is necessary to open the medullary canal with an awl or with a drill bit using power. Then, reduction is performed under visual control and the nail can cross the fracture site. The rest of the procedure is as previously described (Fig. 16.15)

16.2.13 Postoperative Care

AP and lateral X-rays are taken and the forearm is elevated. It is important to ensure that fingers can be actively mobilized throughout a full range of motion (particularly in extension) without eliciting pain. Close observation for possible compartment syndrome must be undertaken. A light dressing is applied and replaced

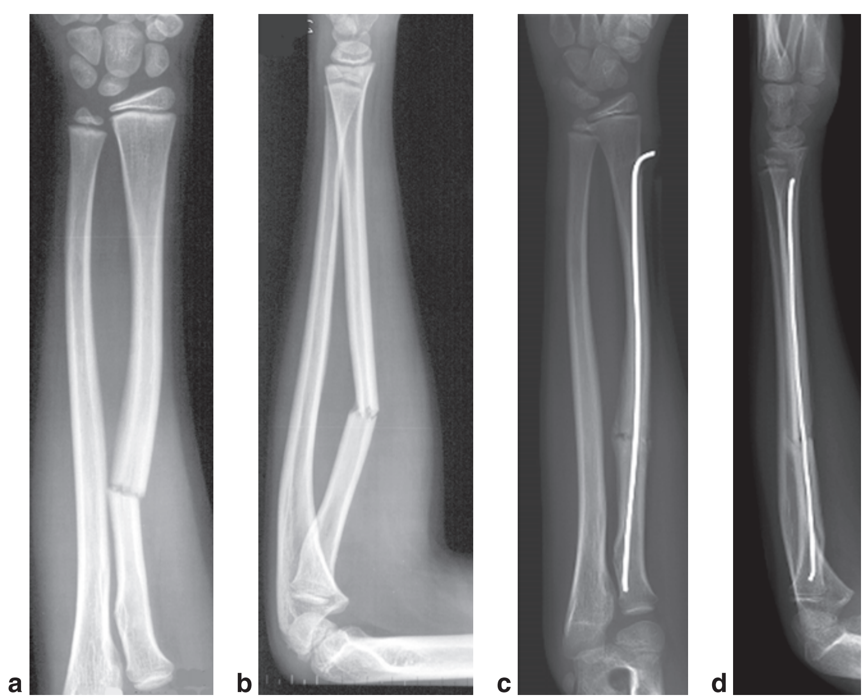


Fig. 16.13 A 13-year-old boy with an isolated fracture of the proximal third of the radius. The AP view shows a significant amount of rotation at the fracture site (**a**) and the lateral view an angulation of the fracture (**b**). During the reduction maneuvers performed under general anesthesia, both fragments overlapped and became unreducible. Direct approach was necessary to facilitate FIN using a 2 mm stainless steel nail. One month after surgery, there is radiographic evidence of initial callus formation (**c**, **d**)

Fig. 16.14 A 4-year-old girl with a Monteggia fracture/dislocation (**a**). Reduction of the radial head, antegrade FIN for the ulna, 1.5 mm stainless steel nail, and long-arm cast. Note that the concave side of the ulnar nail faces the radius, which maintains reduction of the radial head (**b**, **c**). Five weeks later, the fracture is united (**d**). X-ray taken at 1 year (**e**, **f**)

on the second postoperative day. If everything is fine, the child is discharged from the hospital wearing a simple protective sling.

The child rarely needs to go through a rehabilitation program, and is just encouraged to actively mobilize the elbow and the wrist and perform gentle, slow pronation–supination movements.

Both the child and the family are informed that subcutaneous prominence of the nails is absolutely normal and will disappear as soon as the nails are removed. Once the wound has healed, the child is requested to gently mobilize the skin area around the nails to prevent scar tissue from adhering to the sectioned end of the nail.

16.2.14 Medical Treatment

Pain killers, associated or not with antiinflammatories, are prescribed, until complete resolution of pain. For open fractures, prophylactic antibiotics are routinely used.

16.2.15 Protection

Stability is such that cast immobilization is unnecessary. As a rule, the child will wear a simple sling for about 3 weeks, provided that both bones have been treated concomitantly, as recommended. Some surgeons use only one nail and a plaster cast. This does not at all meet the basic principles of FIN, which are that reduction of the fractures is maintained by the tightened interosseous membrane. Inserting a nail in only one bone will not prevent displacement of the fragments in the other bone [19]. Moreover, by doing this, one combines the disadvantages of both methods – incomplete surgical treatment plus cast immobilization [20, 21] – without enjoying any of their benefits.

16.2.16 Resumption of Activities

The child is able to return to school as soon as he/she is back home or after 1–2 weeks (at the most). Even when the dominant limb is involved, handwriting can be resumed within a few weeks. Some children even told us that they had returned to certain sports (e.g., swimming and other individual sports) only 1 month after the injury. Young musicians are able to practice again, very rapidly.

Clinical and radiological follow-ups are scheduled at 3 weeks, 6 weeks, and 3 months postoperatively. Once union is completed, the hardware can be removed.

16.2.17 Implant Removal

The implants are removed later than in other fractures. Removal is performed under general anesthesia, after the sixth postoperative month. As a matter of fact, one must wait until callus formation is initiated, and more important, until cortical healing has occurred. The latter takes longer and is closely related to bone remodeling. Once the nails are removed, the medullary canals are patent again, the bone shafts have their original tubular shape, the cortical bone is strong, and alignment is perfect. The estimated risk of recurrent fracture is significantly reduced, compared to that reported after nonoperative treatment (6–10%) [6, 15].

The procedure can be performed on an out-patient basis using the previous scars. The child is requested to refrain from high-impact and group sports for 2 months to reduce the risk of fracture at the entry hole sites.

16.2.18 Postoperative Follow-Up

Most often, a child with an excellent outcome is not followed-up for more than 1 year and is considered (legally) as permanently healed. However, depending on the child's age or in the presence of a residual angulation or any other complication, a 2-year, radiographic follow-up should be scheduled.

16.3 Complications

16.3.1 Difficult Reduction and Instability

Basically, FIN is a closed reduction technique. Open surgery should only be considered when absolutely necessary, contrary to other treatment methods, which routinely use an open approach [22]. Nevertheless, about 15% of these fractures require a short incision; because one or both fractures cannot be reduced by

Fig. 16.15 A 12-year-old boy with a mildly displaced fracture of both bones of the forearm managed by closed means (**a**, **b**); (**c**, **d**) Plaster cast was removed after 2 months; (**e**, **f**) 3 months later, he again fractured both bones during a fall; (**g**, **h**) He was treated with FIN, using two 1.8 mm stainless steel nails. At 2 months, fractures were almost completely healed. It should be pointed out that open approach was not necessary

closed means after some time has elapsed. This often occurs in proximal fractures where bone fragments fully overlap each other. In the SoFCOT series, a limited approach was used in 13.2% of the fractures, 50% of which involved only the radius and 33% involved both bones.

In 18% of the fractures, the awl was most efficient, avoiding the need for a mini incision. If a limited approach is considered, the tourniquet is inflated and the incision is centered over the fracture site. In the proximal radius, dissection is carried out between muscles of the ventral and lateral compartments. A direct posteromedial approach is used in the ulna. Following evacuation of the hematoma and retraction of muscles with minimal periosteal stripping, two clamps are used to reduce the fracture and allow the nail's crossing of the fracture site under visual control (Fig. 16.16).

16.3.2 Open Fractures

Types I and II open fractures are good indications for FIN. After careful debridement, the fracture is anatomically reduced under visual control. For one bone at least, the tip of the nail can be followed visually through the break in the skin, as it crosses the fracture site. Delayed healing should be expected due to periosteal damage and opening of the fracture site. Very often, the fracture line is still apparent at 3 months, which does not affect the normal healing process.

16.3.3 Implant-Related Problems

The risk of impaction and shortening of fragments is almost nil. Skin irritation (if any) at the entry site is generally due to a faulty technique. Two points must be stressed: (1) In the ulna, the olecranon should be approached posterolaterally as the end of the nail is usually buried in the anconeus muscle (short extensor) (Fig. 16.17); and (2) in the radius, careful attention should be given to nail trimming as residual length is important.

When faced with skin impingement or skin perforation, two options are available depending on the time elapsed: nail shortening, or premature removal of the nails. In the latter case, the child must wear an orthosis or a removable splint during all activities.

16.3.4 Vascular Complications

In isolated fractures of both bones of the forearm, vascular complications from trauma are rare. Early in our experience, intraoperative injury to the radial artery at the wrist occurred in one patient due to mishandling of the awl. This is the reason why we prefer to use a

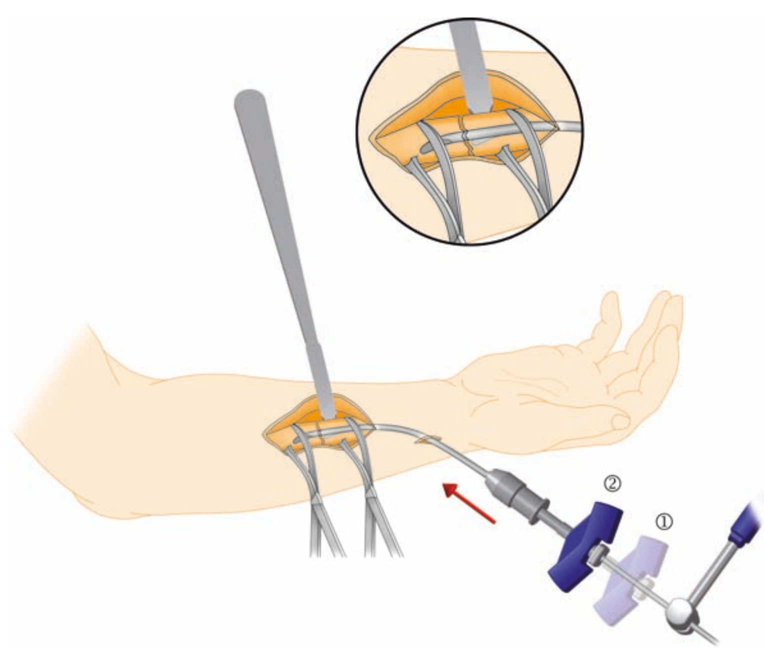


Fig. 16.16 Mini incision in the radius to reduce the fracture under visual control and facilitate the nail's crossing of the fracture site

Fig. 16.17 Skin lesion at the entry site of an ulnar nail that was not trimmed short enough. Note the posterolateral approach to the olecranon

slightly anterolateral approach to the radius, in which the awl can be directed posteriorly.

16.3.5 Compartment Syndrome

After FIN, if the development of a compartment syndrome is suspected or established, the nails protect against potential redisplacement during fasciotomies. Without a plaster cast, subsequent monitoring and care are greatly facilitated. In contrast, if a compartment syndrome is diagnosed after conservative management, it is advisable (for the above mentioned reasons) to perform an FIN concomitantly with fasciotomies.

Some surgeons claimed that FIN was responsible for compartment syndrome, but it seems that repeated, forceful manipulations were used to achieve reduction at any cost [23]. Therefore, in case of difficulty to reduce the fracture, one must not hesitate to open the fracture site for inserting the nail.

16.3.6 Infection

The potential risk of osteomyelitis, particularly in open fractures, cannot be ignored. The cases reported in the literature mainly involve screw plate fixation. Most often, the surgical treatment consists of hardware removal, debridement and local drainage, use of an external fixator if union is not yet achieved, and germ-specific antibiotics. Selection of the treatment method should take into account: the age of the child, the severity of the sepsis, and experience of the surgical team. [22, 24–29].

In our experience, we have had one infection, which resolved after removal of the hardware and antibiotic therapy (less than 0.5% of osteomyelitis) (Case 1).

16.3.7 Joint Stiffness

In children and adolescents, joint stiffness is almost always due to malunion. Therefore, due to the quality of initial reduction, it is infrequently seen with FIN. Restriction of pronation–supination (if any) is due to the loss of the radial bow and failure to bring the interosseous membrane under tension. The postoperative X-ray will often reveal misdirection of the nails. Ten degrees of malunion result in 10° of limitation of range of motion, and little improvement can be expected during the remaining growth period. Therefore, we think that proper orientation of the concavity of the nails is critically important; so is mobilization of the child's forearm through the full range of pronation–supination at the end of the procedure.

16.3.8 Delayed Union and Nonunion

Our series involves more than 300 patients, and no nonunion has ever been experienced. In regards to radiographic healing, we have noticed that, after open surgery or open fracture, the fracture line remains visible longer. This sign of delayed union is generally seen on the side where periosteum has been damaged and can be observed in up to 5% of the patients. Still, whatever the findings, the nails can be safely removed after the sixth postoperative month, as soon as complete union is achieved [3, 26, 28, 30].

16.3.9 Refractures

Since patients treated with FIN are able to return to sports early, they are exposed to the risk of sustaining a new severe trauma. The child presents with a characteristic deformation of the forearm with pain. The X-ray confirms the fracture and shows that nails are bent. If manipulative reduction is obtained under general anesthesia, the initial shape of the nails can be restored, and this may be sufficient to maintain the reduction. In this case, immobilization of the forearm for 4–6 weeks is justified because of mechanical weakening of the construct. But, if reduction is inadequate, one or both nails must be replaced. Patency of the medullary canal and absence of severe displacement facilitate the procedure

(Case 2). We have never experienced implant breakage inside the bone.

16.3.10 Recurrent Fractures Following FIN

We have previously discussed recurrent fractures following nonoperative treatment. Regarding FIN, among all the patients treated before 1987, there were four recurrences between 3 and 6 months after the initial injury (nails being removed), which required a second FIN. An open approach was not necessary; since the medullary canal was patent, which is not the case when manipulative reduction is initially performed (Case 3). Since 1987, we have got into the habit of leaving the nails in situ for more than 6 months. To date, no new cases of recurrent fracture have been observed. Some hyperactive patients sustained a second forearm fracture in a different location and were treated accordingly.

We believe that FIN protects the bone by promoting bone union. First, the reduction is almost always anatomic, since overlapping and angulation preclude proper positioning of the nail. Secondly, patency of the medullary canal is maintained, more especially as the nail prevents residual translation. Lastly, as the nail remains in situ for 6 months, it leaves enough time for cortical bone to remodel and unite.

16.3.11 Difficult Implant Removal

Because of the small diameter (≤2.5 mm) of the nail, removal is generally very easy, provided that the end of the nail is proud enough and significant periosteal reaction has developed. For the radial incision (using the previous scar), it is advisable to inflate the tourniquet, to avoid injury to the sensory branch of the radial nerve and to facilitate access to the radius. A small curved osteotome or a rongeur can be helpful to clean the nail of bone tissue and to make removal easier [31].

16.4 Indications

16.4.1 Amount of Displacement

Amount of initial displacement is the most commonly used criterion (65%) [1, 32–40]. If there is no contact between the bone fragments, the fact that the periosteum is torn makes these fractures highly unstable and amenable to FIN (Case 4, Fig. 16.21). Another criterion is the duration of cast immobilization with nonoperative treatment: In such cases, it will be 3 months for an adolescent, which is quite a long time, particularly if the dominant limb is involved. Where contact between bone fragments is maintained, obtaining a perfect reduction is mandatory in older children, who have a diminished remodeling capacity – correction of malunion is only 1° per year [41–43]. Isolated greenstick and plastic-bowing fractures must definitely be managed by closed means.

16.4.2 Age of the Patient

The patient's age is the second most important criterion (59%). Children under the age of 6 years have a bone remodeling capacity of up to 10°, and are therefore, almost always treated by closed means, whatever be the severity of the displacement [42]. In older children, the indication for FIN depends on several factors, including the amount of displacement, reducibility of the fracture, and the chances of achieving initial stability. Therefore, bone remodeling capacity will be the determining factor for the final decision [41, 43, 44]. In adolescents, where anatomic reduction is mandatory and cast immobilization undesirable, FIN is often privileged.

16.4.3 Failure of Nonoperative Treatment

As previously discussed, secondary displacement with plaster support is an indication for FIN.

16.4.4 Multiply Injured Patients

For easily understandable care and monitoring reasons, multiply injured young patients with both-bone forearm fractures are best managed with FIN.

16.4.5 Open Fractures

Types I and II open fractures are also good indications for FIN, which allows regular monitoring of skin condition postoperatively.

16.4.6 Compartment Syndrome

Compartment syndrome is best treated with FIN, for the same reasons (postoperative skin care).

16.4.7 Recurrent Fractures

An additional 3-month period of cast immobilization is not well tolerated by adolescents, and this pleads in favor of FIN [45, 46].

16.4.8 Additional Criteria

Certain criteria such as: a dominant upper limb, engaging in specific sports, playing a musical instrument may have to be taken into account in adolescents.

16.5 Contraindications and Limitations

In our experience, the only contraindications to the use of FIN in the forearm have been Type III open fractures and extensive soft tissue damage [47].

As for fractures associated with initial nerve lesions that have a good prognosis, the treatment method is exactly the same as that previously described, irrespective of the neurologic complication.

16.6 Case Reports

16.6.1 Case 1

An 11-year-old boy with a closed middle third fracture of both bones of the forearm was initially treated by closed means. A secondary displacement was managed with FIN, using two, 2 mm titanium nails. The X-ray taken at 1 month showed ulnar malunion and worrying osteolytic lesions in the radius, both at the fracture site and entry hole (a, b). Slight pus discharge from the wound revealed Staphylococcus aureus. Still, the child's general condition was good; he did not complain of anything and had no biological inflammatory syndrome. After immobilization, healing progressed normally, as seen on the X-rays taken at 4 months (c, d). Upon removal of the nails, acute pus discharge from bone revealed the presence of Staphylococcus aureus. Local irrigation was performed (e) and specific antibiotics were given for a total of 6 weeks. After that, the fracture healed uneventfully (f, g). Unfortunately, the child sustained a fracture of the distal one-fourth of the forearm 18 months later (Fig. 16.18).

Note: Osteomyelitis that was diagnosed at a later time was likely present after surgery, but it did not interfere with the healing process.

Fig. 16.18 Case 1

16.6.2 Case 2

A 13-year-old boy with a distal fracture of both bones of the forearm and skin lesion (Gustilo Type II) on the ulnar side (a, b). The child was operated on under general anesthesia: After debridement of the ulnar fracture site, antegrade FIN was performed. The radial fracture was irreducible and required open surgery. Reduction was maintained using a short flexible 2.5 mm titanium nail which was inserted retrograde to take advantage of the concavity of the ulna. Note the bone defect in the ulna (c, d). (e, f) four months later, the X-ray showed bone union; and it was decided to remove the nails at 6 months. (g, h) In the sixth month, before the nails were removed, the child fell heavily and refractured both long bones. During the fall, both nails sustained severe bending (about 90°). (i, j) The nails were straightened under general anesthesia and left in situ. (k) Two months later, both fractures were found to be healing normally. (l) Eight months later, the fractures were united and the nails could be removed (Fig. 16.19).

Note: Refracture sustained during high-energy trauma with the nails in situ can be reduced by closed means.

Fig. 16.19 Case 2

Fig. 16.19 (*cont.*) Case 2

16.6.3 Case 3

An 11-year-old girl with fractures of both bones of her left forearm (a, b). X-ray was taken 1 month after combined antegrade/retrograde FIN using two 2 mm stainless steel nails which were removed 2 months postfracture (c, d). Six months later, patency of the medullary canal was not restored (e). At 8 months, the child sustained a recurrent fracture resulting from a fall (f), which was treated with FIN, using two 2 mm stainless steel nails. Union was achieved by 2 months (g) and both nails were removed. Unfortunately, the child fell again 10 days later and refractured her forearm (h). A third FIN was performed using two 2.5 mm stainless steel nails (i, j). The nails were left for 3 months and removed after sound cortical and medullary union was achieved (k, l) (Fig. 16.20).

Note: We now know that the nails were removed much too early and that it is important to wait until the medullary canal is patent again. As far as the third FIN procedure is concerned, the ulnar nail inserted through the olecranon was responsible for skin problems, which gave rise to further complications.

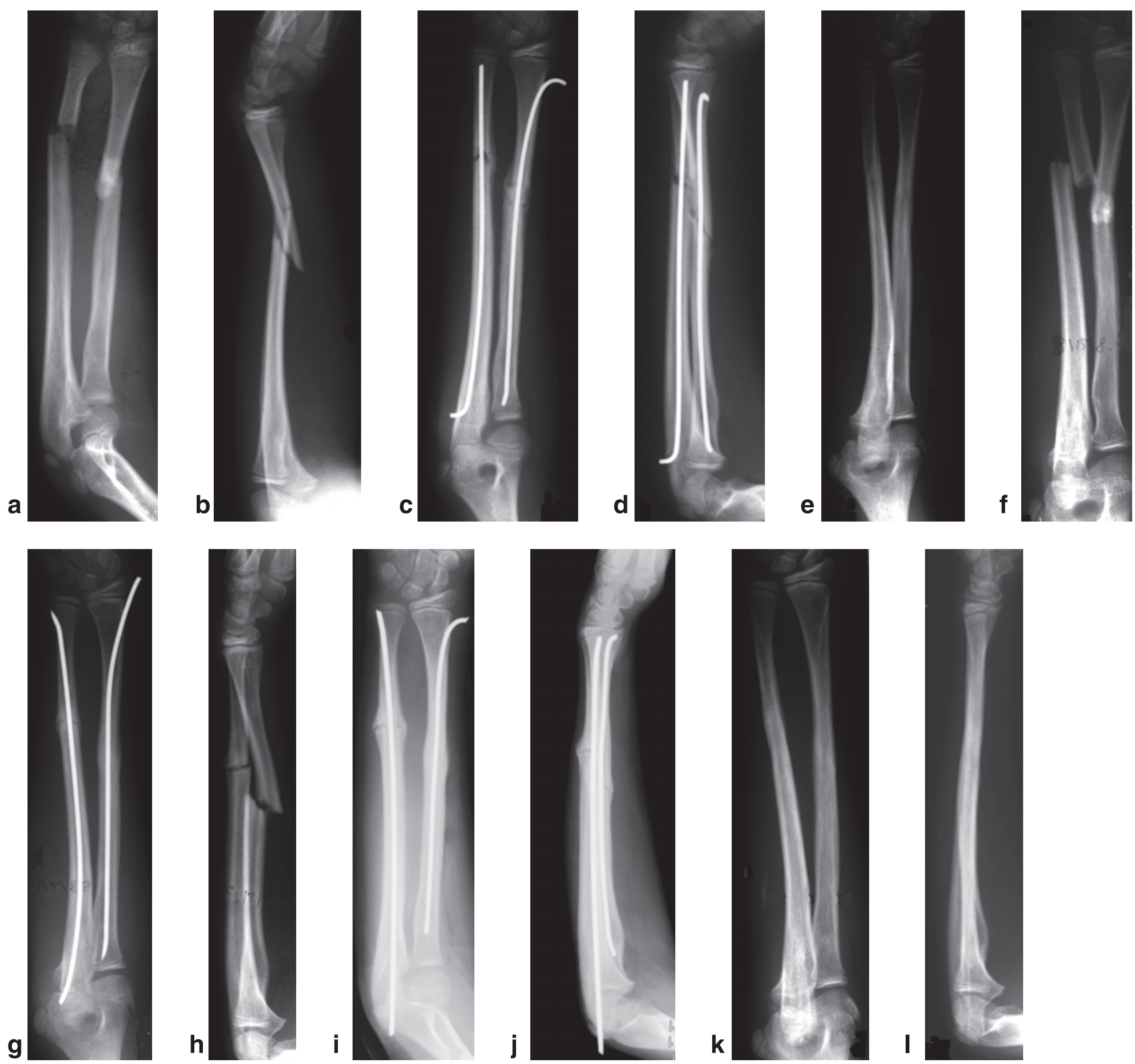


Fig. 16.20 Case 3

16.6.4 Case 4

An 11-year-old boy with a displaced middle-third fracture of both bones of the forearm treated with FIN using two 2.5 mm stainless steels (a, b). (c, d) Excellent outcome at 5 months – bone union, function near normal. (e, f) Nine months later, the nails were removed and the result was excellent (Fig. 16.21).

Note: This is a typical image: The concave side of the radial nail faces the ulna and vice versa.

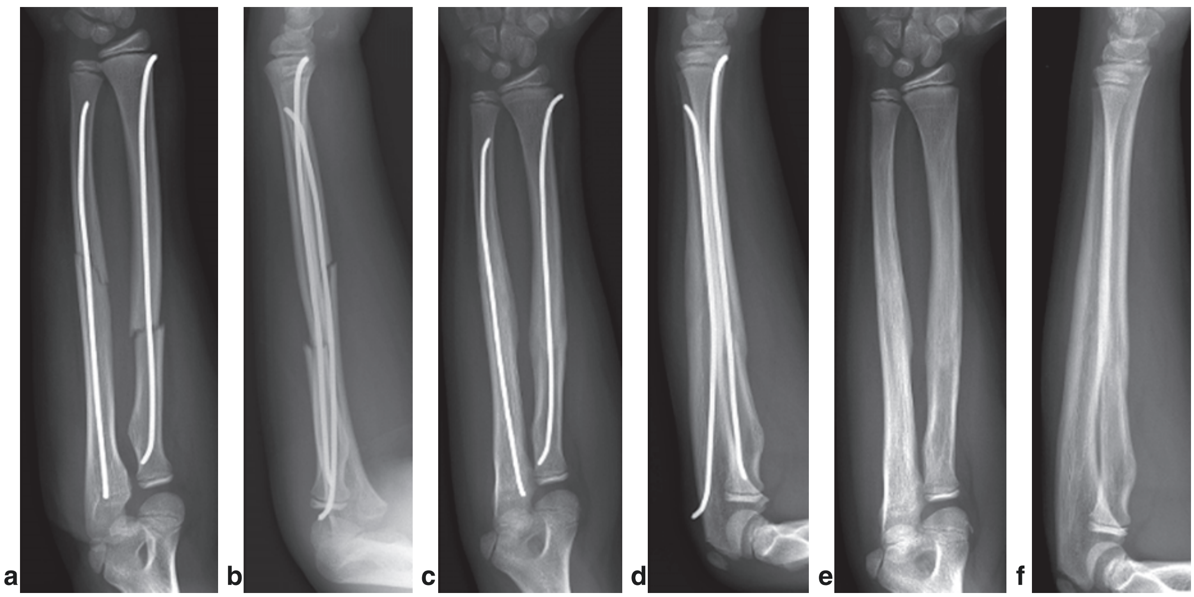


Fig. 16.21 Case 4

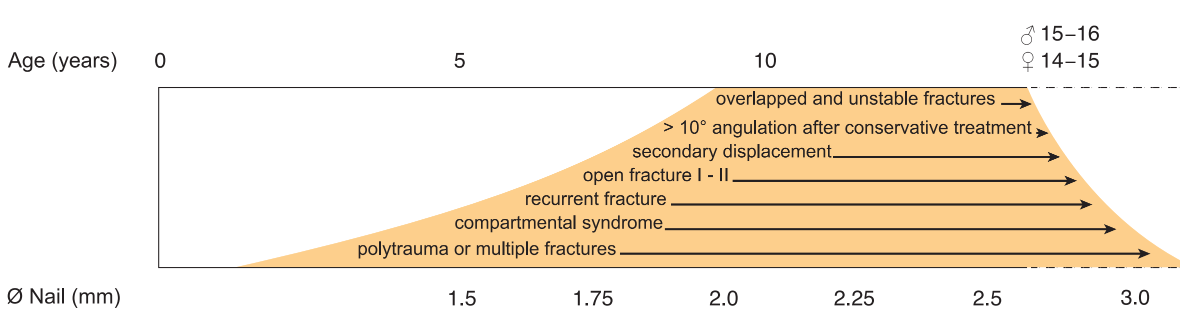
16.7 Six Key Points

- Each fractured bone must be nailed: both radius and ulna.
- Nails must be contoured so that concavities face each other.
- The ulnar nail should always be inserted through the posterolateral aspect of the olecranon.
- The nail should always be advanced across the fracture site with the help of a slotted hammer.
- At end of the procedure, the forearm must be moved through its full range of pronation–supination.
- Hardware should be left in situ for 6 months to prevent recurrence of fractures.

16.8 FIN and Forearm Fracture: Postoperative Management in the Abence of Complications

Day 0	• Postoperative AP and lateral radiographs • Careful monitoring: watch for compartment syndrome • Operated arm is elevated • Pain killers ± antiinflammatories • Patient is allowed to get out of bed using a protective sling
Day 2	• First dressing • Rehabilitation: active mobilization of the upper limb, elbow and wrist • Discharge with instructions if healing progresses normally • Early return to school
Three to six weeks postop.	• Clinical and radiological (AP and lateral) follow-up • Sling removed at 3 weeks • Gradual, limited return to sports
Three to six months postop.	• Clinical and radiological (AP and lateral) follow-up • Nail removal can be considered from the sixth month • Return to full sports participation
Eighteen to twenty-four months postop.	• Clinical and radiological (AP and lateral) follow-up

16.9 FIN Indications: Forearm Fractures



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Metacarpal and Phalangeal Fractures

17

Stéphane Barbary and Gilles Dautel

17.1 Fracture of the Base of the Thumb

17.1.1 Mechanisms of Injury and Classifications

Fracture of the base of the thumb is typically the so called "Boxer's fracture," which results from striking a solid object with a clenched fist and the thumb folded into the palm. Metacarpal fractures involve mainly the base of the thumb and the neck of the fifth and fourth metacarpals [1]. The fracture generally propagates across the growth plate (Salter II fracture). Displacement occurs in the direction of palmar flexion. Bone remodeling capacity in this region is excellent, and indications for flexible intramedullary nailing (FIN) are scarce. Angulation of up to 50–60° is acceptable in a child who has at least 3–4 years of growth remaining. Retrograde intramedullary wiring is necessary where severe instability precludes nonoperative management. Jehanno and Iselin recommend wiring in pure metaphyseal fractures and Salter II fractures with a lateral Thurston-Holland fragment [2]. The rare intra-articular fractures (Salter III and IV) that are encountered are surgically managed to restore a perfect articular congruity.

In France, antegrade intramedullary wiring of the first metacarpal has been popularized by Kapandji, who used to insert one single wire through the trapeziometacarpal joint. The concept of FIN based on the placement of two contoured wires, which leave the adjacent joints completely free was described in the literature later on [3]. This technique is particularly well suited for long bones of the hand [1].

17.1.2 Retrograde FIN

17.1.2.1 Patient Positioning

General anesthesia is used in children less than 13 years of age; regional anesthesia may be proposed to older children. The child is positioned supine on the operating table, with the injured limb placed on an arm table. A tourniquet is placed at the upper arm. A sterile drape is laid over the entire forearm including the elbow. It is recommended to stand at the end of the table so as to position the image intensifer at the patient's feet, parallel to his/her body [4].

All checks are performed using the image intensifier: AP views (Kapandji views) and lateral views in pronation and supination positions.

17.1.2.2 Closed Reduction

Adequate reduction is no doubt the key to a straightforward procedure. In case of fragment overlap, realignment can be achieved by first applying axial traction to the thumb column. Then, the surgeon firmly holds the metaphysis with the thumb and index finger and performs appropriate maneuvers to achieve reduction in all planes. Finally, pressure is applied along the axis of the thumb column to secure the reduction before initiating the FIN procedure (Fig. 17.1).

P. Lascombes, *Flexible Intramedullary Nailing in Children*,
DOI: 10.1007/978-3-642-03031-4_17, © Springer-Verlag Berlin Heidelberg 2010

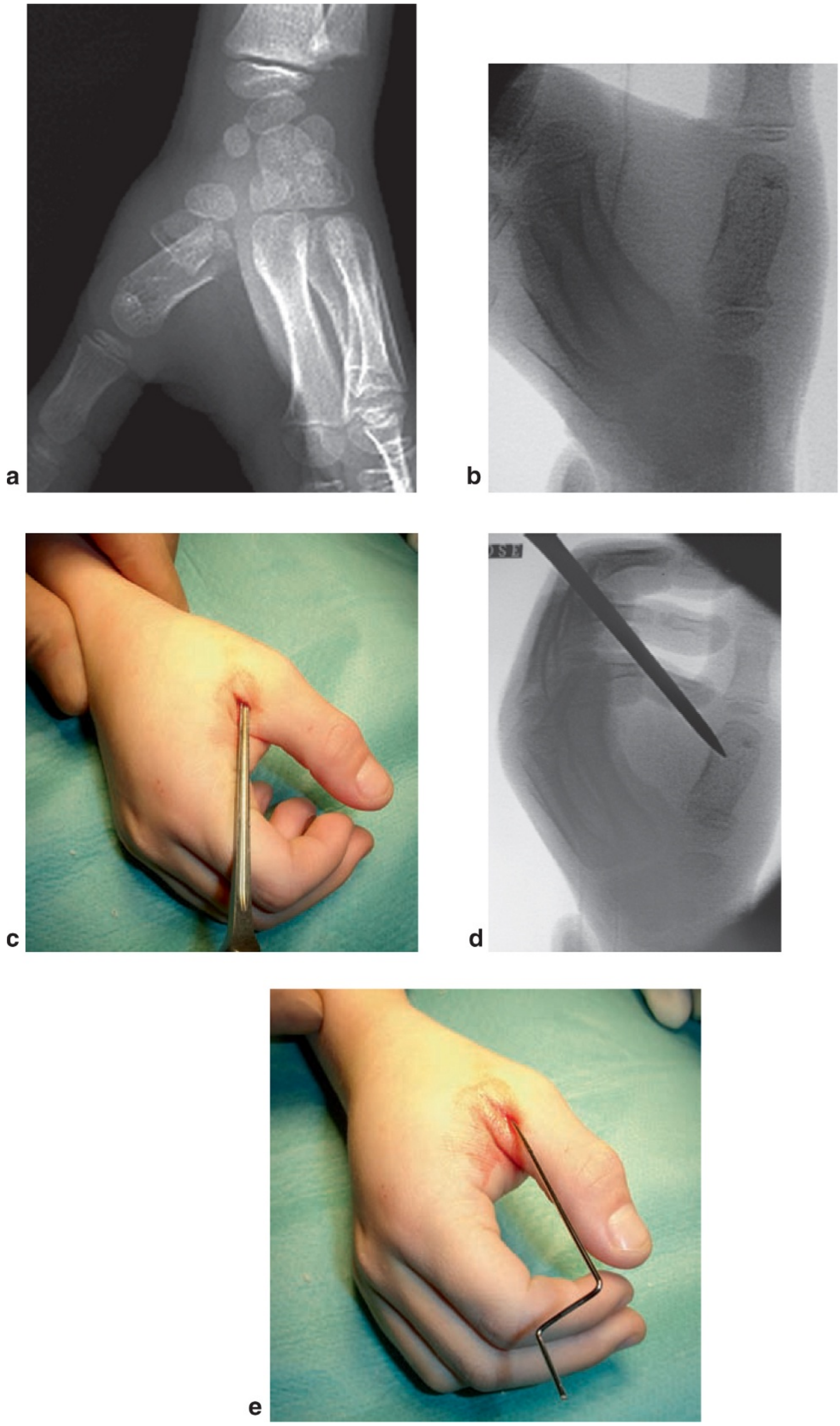

Fig. 17.1 (**a**) Fracture with overlapping at the base of the thumb; (**b**) reduction of the fracture site; (**c**) insertion of the awl into the metaphysis; (**d**) fluoroscopic check; (**e**) insertion of the first bayonet-shaped wire

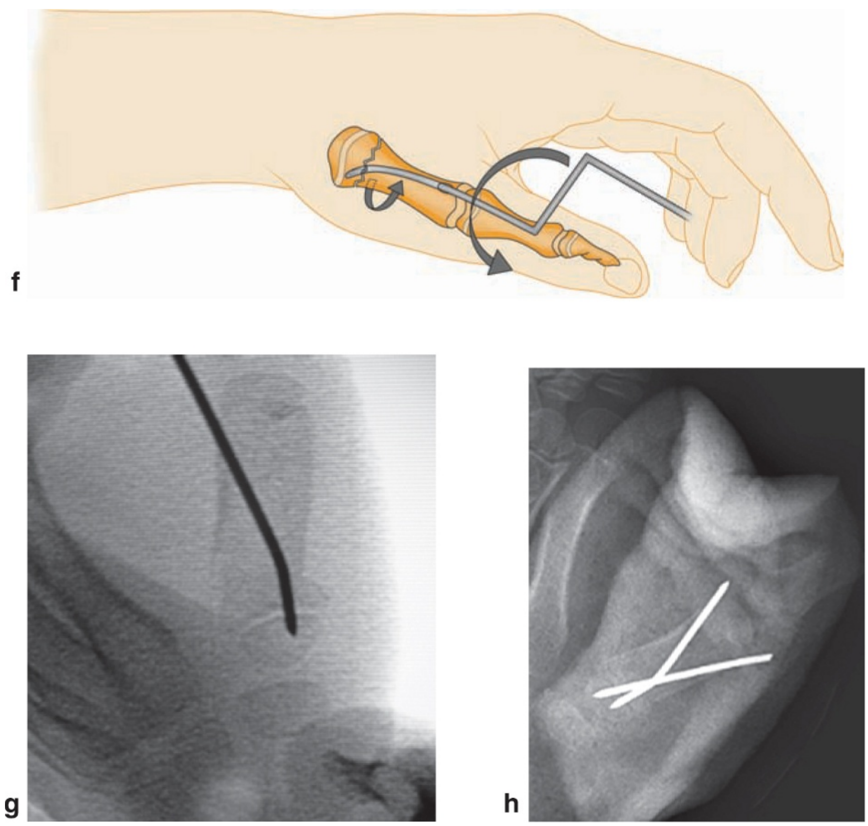

Fig. 17.1 (*cont.*) (**f**) Nail shaped into a Z-configuration; (**g**) position of the first nail is checked under fluoroscopy; (**h**) final position of both wires is checked under fluoroscopy

17.1.2.3 Selection and Preparation of the Implants

The diameter of the wire must be slightly larger than that of the cortex. Considering the children's age range (usually 7–13 years), the most commonly used diameters are 1.0–1.2 mm, rarely 1.5 mm.

17.1.2.4 Surgical Approach

Two lateral incisions about 7 mm long are sufficient. They are performed on either side of the head of the first metacarpal. Blunt scissors dissection is then carried down to the bone surface. An oblique entry hole is made with an awl for wire insertion (Fig. 17.1). The wires are slightly curved to avoid penetration of the opposite cortex. The tip of the wire passes through the growth plate and anchors in the base of the thumb. One useful trick when hand pushing the wires without the help of an instrument is to shape them into a Z-configuration (bayonet shape). Otherwise, a used needle holder (or a small handle) is recommended. It makes it easier to rotate the wires, push them, and avoid confusion. When preparing the entry site for the ulnar wire, care must be taken to preserve the insertion of the medial collateral ligament and avoid damage to the ulnar nerve, which is critically important for sensation in the ulnar half of the thumb.

17.1.2.5 Final Reduction

As soon as the first wire is anchored in the base of the thumb, a slight rotation may assist in completing the reduction, as is done in the femur with contoured elastic intramedullary nails.

17.1.2.6 Postoperative Care

The wires are trimmed to the desired length and buried to avoid skin irritation. An absorbable suture is often used in children. Postoperative care consists in a small compressive dressing and a plaster splint that is worn for about 10 days to relieve pain. This way, the thumb column is immobilized and motion of the interphalangeal joint is maintained. After that, a thumb abduction splint that opens the thumb web space is applied; this can be performed as a day case using antalgics and antiinflammatories. This splint will be worn for 2–3 weeks. It is advisable to remove the wires before the eighth week.

17.2 Fracture of the Fifth Metacarpal

17.2.1 Mechanism of Injury and Indications

This fracture that typically occurs when punching a wall generally involves the neck of the fifth metacarpal, and there is palmar displacement of the metacarpal head. Conservative management is advocated as malunion is particularly well tolerated. As far as we are concerned, we consider that up to 30–40° of angulation is acceptable. Other authors will surgically manage fractures with more than 70° of angulation [5]. Malrotation with finger overlapping its neighbor when making a fist is an absolute indication for surgery. In fractures of the fifth metacarpal shaft, the use of FIN minimizes the potential for skin and tendon adhesions, and cosmetically disfiguring scars. Furthermore, the rigidity achieved with an FIN construct is comparable to that provided by fixation plates [1, 4], with the same advantage of allowing early mobilization. Likewise, an equal rigidity is provided by FIN using two wires with opposing curves and by a "bouquet" osteosynthesis [6], as described by Foucher [7, 8].

17.2.2 Antegrade FIN

17.2.2.1 Anesthesia

In this type of fracture also, we prefer to use general anesthesia. However, in older children, the procedure may be performed under regional anesthesia. An ulnar block at the wrist provides effective anesthesia of the affected area, but it prevents the use of a tourniquet. Initially, for the first cases, it is recommended to use a complete axillary block.

17.2.2.2 Patient Positioning

The child is positioned supine on the operating table, with the injured limb placed on an arm table. The surgeon should stand at the patient's head to position an image intensifier at the foot of the table, parallel to the child's body, in front of him/her. The following views are needed intraoperatively: pronation AP, supination AP, pronation oblique, supination oblique, and true lateral. The true lateral view is most useful: dorsal crossing of the fracture site will only appear on a true lateral radiograph.

17.2.2.3 Reduction

Reduction of fracture of the metacarpal neck is performed using the Jahss method [9] (Fig. 17.2). The Jahss maneuver involves full flexion of the metacarpophalangeal joint to bring the base of P1 below the metacarpal head, followed by upward pressure along the proximal phalanx to push the metacarpal head in a dorsal direction. The same reduction method is used in fractures of the metacarpal shaft. In the rare cases, where manipulative reduction is unsuccessful, a limited open approach will be helpful.

a

Fig. 17.2 Positioning for treatment of fracture of the fifth metacarpal neck (**a**)

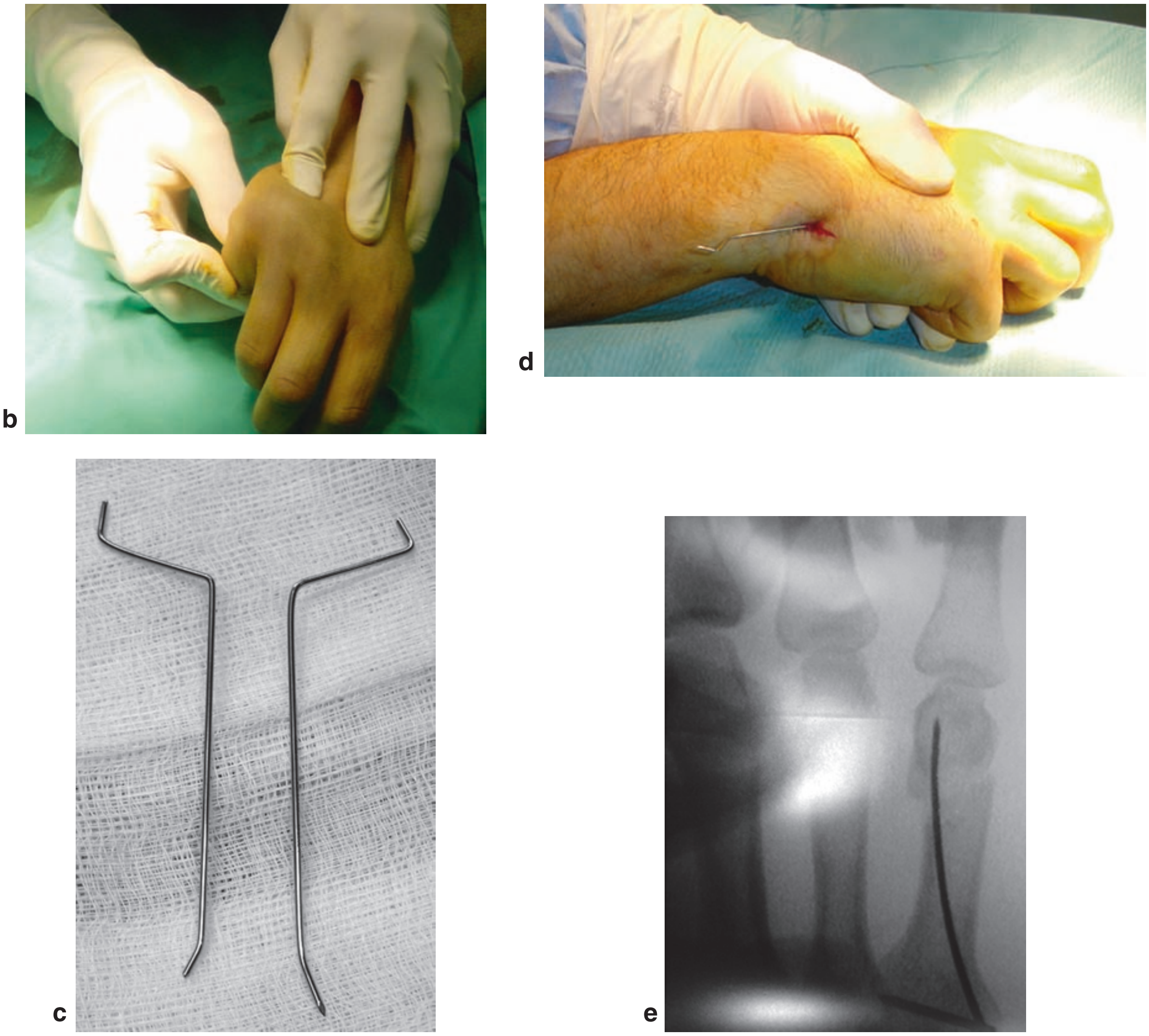

Fig. 17.2 (*cont.*) (**b**) Jahss reduction method; (**c**) both wires are shaped into a Z-configuration; (**d**) insertion of the wire under image intensifier control (**e**)

17.2.2.4 Selection and Preparation of the Implants

We are personally using 1.2–1.5 mm slightly curved K-wires that we shape into a Z-configuration to facilitate placement.

17.2.2.5 Surgical Approach

The posteromedial aspect of the base of the fifth metacarpal is approached through a 10–20 mm horizontal incision, taking care to avoid damage to the nearby dorsal sensory branch of the ulnar nerve. An entry hole is created with the awl in the dorsoulnar aspect of the metacarpal bone, and both wires are pushed by hand or with a used needle holder (or a small handle). The bayonet shape of the wires greatly facilitates insertion. As mentioned above, a true lateral view should be taken to ensure that neither wire has crossed the fracture site dorsally (Fig. 17.3).

17.2.2.6 Final Reduction

Rotating the first wire 90° may help complete the reduction, taking great care not to cause rotational malalignment.

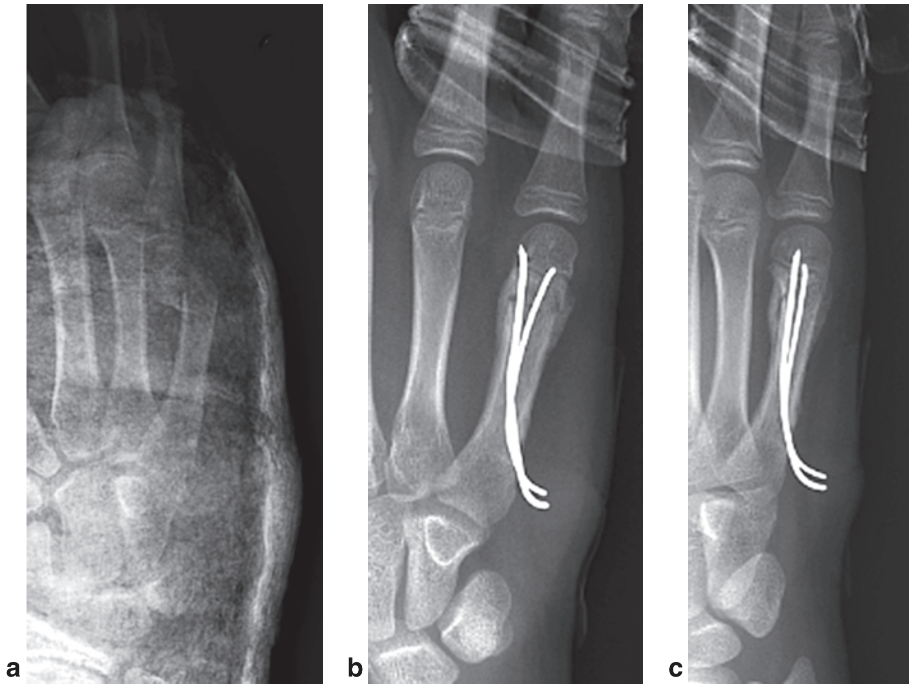

Fig. 17.3 A 14-year-old boy with secondary displacement (with plaster support) of fracture of the neck of the fifth metacarpal (**a**); unipolar antegrade flexible intramedullary nailing (FIN) was performed using two 1 mm stainless steel wires. Union was achieved at 1 month (**b**, **c**) [courtesy of P. Lascombes]

17.2.2.7 Postoperative Care

The wires are carefully trimmed and buried. Wire tips may be left 5 mm proud of the bone surface as removal can sometimes be difficult. A simple compressive dressing is applied. Immobilization is unnecessary; in a few cases, only syndactyly of the ring and small fingers is performed. In contrast, mobilization of the digital chains is highly recommended to prevent stiffening, which, however, is rarely seen in children.

17.3 Fracture of the Fourth Metacarpal

The mechanism of injury is exactly the same as in fracture of the fifth metacarpal, but the incidence rate is lower. The reduction and fixation methods are identical, except that the incision should be made on the radial side of the hand. Postoperative care also is identical (Fig. 17.4).

Fig. 17.4 **a**, **b** Fracture of the neck of the fourth and fifth metacarpals in a skeletally mature adolescent;

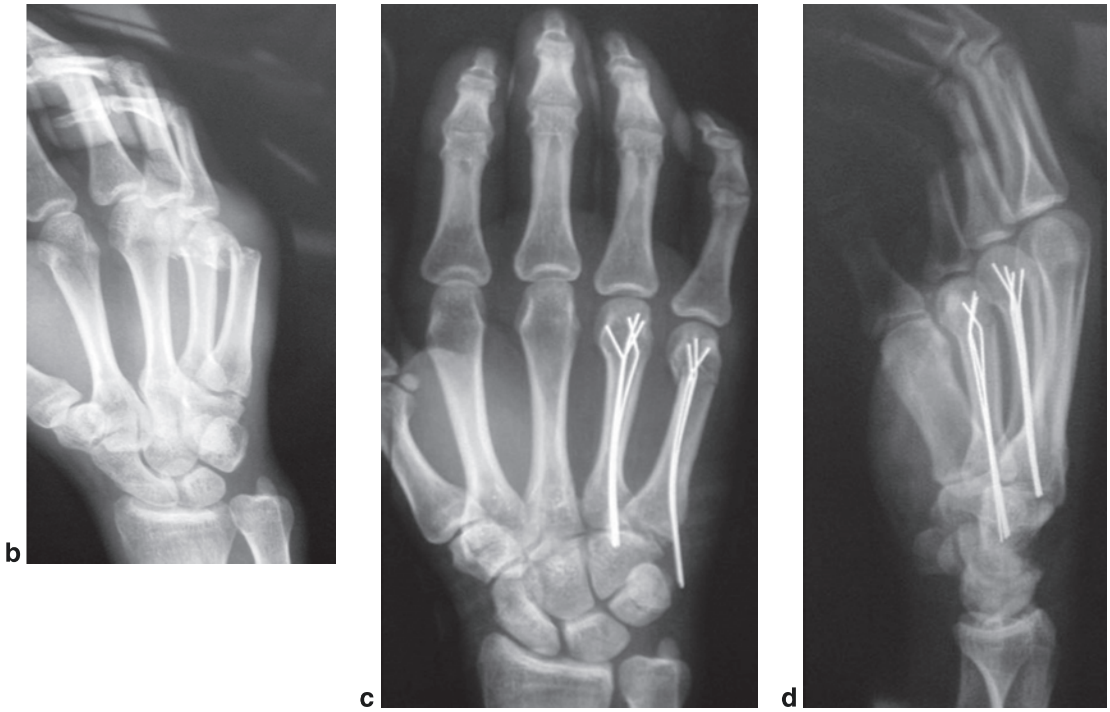

Fig. 17.4 (*cont.*) **c**, **d** antegrade FIN using the "bouquet" technique according to Foucher

17.4 Fracture of the Second Metacarpal

The mechanism of injury is the same as in fracture of the fourth or fifth metacarpal, but the incidence rate is even lower. In children, it is managed under general anesthesia or complete axillary block. Pure local anesthesia is not suitable for this fracture. Reduction is also performed using the Jahss technique. The fixation principle is identical. A horizontal incision is preferred for cosmetic reasons. It is centered over the base of the second metacarpal, and is only 10–20 mm long. The surgeon should be careful to avoid damage to the sensory branches of the radial nerve and vascular structures (there are numerous and relatively large veins in this region). An entry hole is created with the awl in the radial cortex of the base of the second metacarpal. The awl should be directed toward the medullary canal. Then, both wires are advanced as previously described for fractures of the neck of the fifth metacarpal (Fig. 17.5).

Fig. 17.5 Wire construct for fracture of the neck of the second metacarpal

17.5 Phalangeal Fractures

This technique generally yields excellent results in the proximal phalanx, particularly in transverse or short oblique fractures of the base of the phalanx. It is less suited for treatment of comminuted, long oblique, spiral fractures, and fractures of the middle phalanx [9, 10, 11].

Patient positioning is identical to that used for management of metacarpal fractures. The hand is placed on folded towels with palm facing downwards. While general anesthesia is mandatory in young children, regional or even local anesthesia may be used in adolescents. Reduction is performed by applying traction along the axis of the ray together with external maneuvers. In difficult or oblique fractures, it may be necessary to use lion forceps percutaneously. A 5 mm incision is made along the edge of the head of the phalanx, and an entry hole is created with the awl. Two 0.8 mm wires are inserted under fluoroscopic guidance. As it is quite difficult to advance a wire while maintaining the reduction, better not try to reduce the fracture before one wire at least has reached the fracture site. Fixation of fracture of the base of the proximal phalanx may be achieved with one single wire (Fig. 17.6). In case two wires are necessary, their diameter should not exceed 0.6 or 0.8 mm to fit within the narrow shaft of the phalanx (Fig. 17.7). The wires are trimmed and buried as they must not preclude mobilization of the proximal interphalangeal (PIP) joint, which is extremely prone to stiffness, and contributes 75% of the finger curl motion.

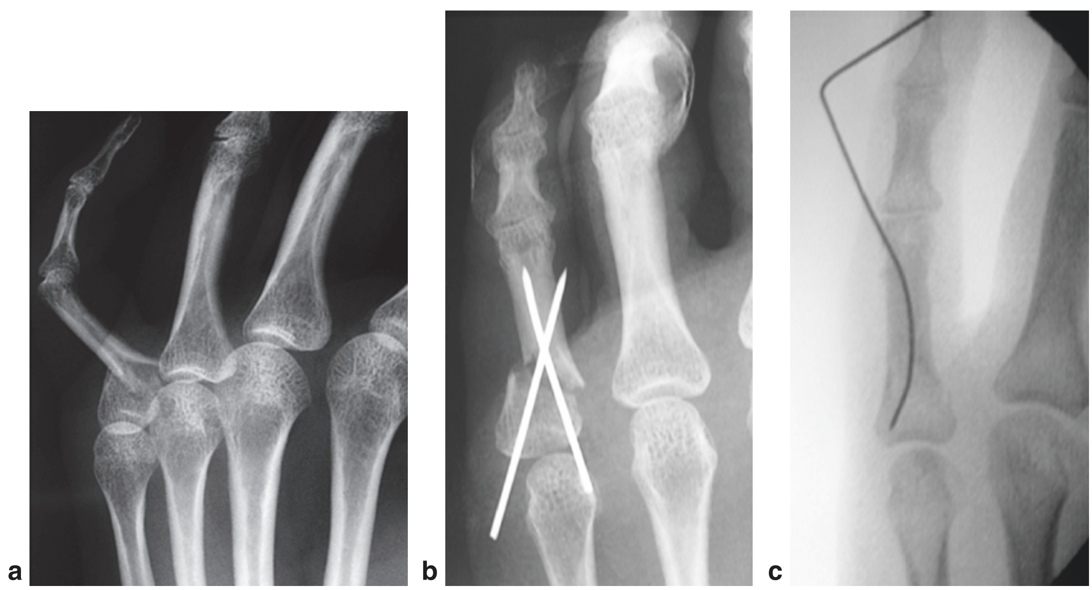

Fig. 17.6 (**a**) Fracture of the base of the proximal phalanx of the fifth metacarpal; (**b**) poor construct with wires placed in a cross pattern: inadequate reduction and impingement of one of the wires upon extensor tendons; (**c**) revised on the eighth postoperative day with retrograde FIN using one single wire: control X-ray shows perfect reduction of the fracture

Fig. 17.7 **a**, **b** Four-part fracture of the shaft of the proximal phalanx of the thumb; **c**, **d** bipolar antegrade FIN and plaster cast

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18 Femoral Fracture

Pierre Lascombes and Jean-Damien Métaizeau

18.1 General Epidemiology

The second most common location of diaphyseal fractures in children is the femur, with prevalence in boys (sex ratio is M2.5:F1). Femoral fractures in children have varying etiologies:

- Birth trauma.
- Child abuse: Silverman syndrome.
- Road traffic accident.
- Fall from a height.
- Sports accident.
- Pathological fracture (tumor, osteogenesis imperfecta, cerebral palsy [CP], etc.).

In children less than 6 years of age, the two major causes are falls (50%) and abuse (30%). In 75% of the children older than age 6, it is road traffic accidents.

18.1.1 Mechanisms of Injury and Classifications

As cortical thickness index increases with age, in adolescents femoral fractures result from high-energy trauma, whereas in small children, a moderate impact is sufficient to fracture the femur.

Femoral fractures can be classified according to anatomic location and pattern as: proximal shaft, midshaft, distal shaft fractures that may be transverse, oblique, spiral, or comminuted. We shall also discuss supracondylar fractures, which are successfully treated with flexible intramedullary nailing (FIN). It should be pointed out that femoral neck fractures are a contraindication to this method with the exception of a few undisplaced basal neck fractures (Fig. 7.3a).

Femoral fractures are usually severely displaced:

- *Proximal third:* the proximal fragment is pulled into flexion, abduction and external rotation, and the distal fragment is in adduction and medial rotation.
- *Middle third:* the fragments are often properly aligned but with considerable overlap, with the proximal fragment positioned anterior to the distal one.
- *Distal third:* displacement of the distal fragment mainly occurs in flexion due to the pull of the gastrocnemius.

18.1.2 Diagnosis

Most femoral fractures are easily diagnosed from clinical and radiographic findings. Only hairline fractures in infants may be difficult to spot with X-rays. As a fractured femur is a serious injury, it is important to always look for associated lesions.

18.1.3 Emergency Procedure

Recovery room care includes continuous monitoring of temperature, hemodynamics and gas exchange, central venous catheterization, and administration of antalgics.

In small children, femoral nerve block facilitates immediate immobilization in a Bryant-type frame, with the lower extremity placed in 90° of flexion at the hip. Skin traction (applied parallel to the bed plane or using a splint) may be included in the normal care process before surgery.

Tibia pin traction is rarely necessary.

P. Lascombes, *Flexible Intramedullary Nailing in Children,*
DOI: 10.1007/978-3-642-03031-4_18, © Springer-Verlag Berlin Heidelberg 2010

18.2 Retrograde FIN for Mid-Shaft Fractures

18.2.1 Anesthesia

In children, the procedure is always performed under general anesthesia associated or not with femoral nerve block.

18.2.2 Patient Positioning

Proper patient positioning on the operating table is essential. The use of a fracture table, which would seem logical in the majority of cases is not an absolute requirement in small children who may be simply positioned supine on a standard operating table. We personally find it easier to place the contralateral limb on a Goepel leg holder to allow positioning of an image intensifier to obtain lateral views, but of course, it is just a matter of surgeon preferences. The C-arm is slightly inclined to make room for a second image intensifier for AP views. It is easy to find appropriate size traction boots for adolescents, but this accessory is rarely available in very small sizes (for small children). One solution consists in using a Velpeau® bandage for protection of the child's foot and a second one that is attached to the traction holder to firmly maintain the foot on the holder.

18.2.3 Closed Reduction

Closed reduction is achieved by applying axial traction to the lower limb, with or without reduction maneuvers according to the displacement of bone fragments. The fragments must be completely disimpacted to allow progression of the nails. Reducibility of the fracture should be assessed prior to draping.

18.2.4 Image Intensifier

Although the use of two image intensifiers is not mandatory, it is highly recommended as it dramatically reduces operative time and radiation exposure. The image intensifier used for AP views is pushed aside during draping. Then, it is covered with a sterile cover and replaced. The surgeon has just enough room to perform FIN in good conditions (Fig. 18.1).

18.2.5 Operative Field

The operative field should include the nail entry points, the fracture area in case an open approach is required, either for reducting the fracture if not possible by closed means or for driving the nails across the fracture site. Additionally, the surgeon must provide for a

Fig. 18.1 Patient positioning on a fracture table for treatment of a femoral fracture using two image intensifiers. It is also possible to use only one image intensifier for the AP views and then rotate the C-arm for the lateral views

subtrochanteric access in case antegrade or combined antegrade/retrograde FIN is decided (Fig. 18.2).

18.2.6 Selection and Preparation of the Implants

The surgeon must select the largest diameter nail that can be accommodated. The appropriate size is determined by measuring the diameter of the medullary canal on a radiograph: nail diameter = 0.4 × diameter of medullary canal or = diameter of medullary canal/2-1 mm. Proper nail selection is critically important in the femur, which is subjected to extremely high forces. Selection of titanium alloy [1, 2] or stainless steel [3, 4] is a matter of personal preferences. Stainless steel is slightly more rigid but less flexible than titanium alloy for same diameter nails. However, stainless steel nails may be more appropriate in adolescents with mid-shaft fractures, as significant moment arm will be put on the device.

Nail diameter is related to the age of the child and the size of the bone:

- 3 mm in a child aged between 6 and 8 years
- 3.5 mm in a child aged between 8 and 10 years
- 4 mm in a child older than age 11

In nails with a fixed length, length is measured between the physis of the greater trochanter and the distal physis (Fig. 18.3).

Nails are contoured according to the type and location of the fracture. In any case, the tips must be blunt or tapered and slightly curved (30–40°) over a length of 5–8 mm. Furthermore, it is essential that contouring and bending are performed in the same plane to achieve a uniform concave curve. Some nails are designed with a laser engraved line, which avoids handling errors. Only mild contouring is required but it is important that it creates a very smooth curve. Should minor adjustments be necessary, they will be made by forcing the nail against the wall as it is advanced through the medullary canal.

18.2.7 Surgical Approach

For retrograde FIN, two incisions are made (medially and laterally) in the distal metaphysis immediately below the hard cortical bone area, at some distance from the physis (Fig. 18.4). The skin incisions begin at the planned entry points and extend 20–30 mm distally to

Fig. 18.2 Ideal insertion zones for medial/lateral distal nails and subtrochanteric lateral nails. Note the high position of bipolar retrograde flexible intramedullary nailing (FIN) (fracture at the middle-proximal third junction)

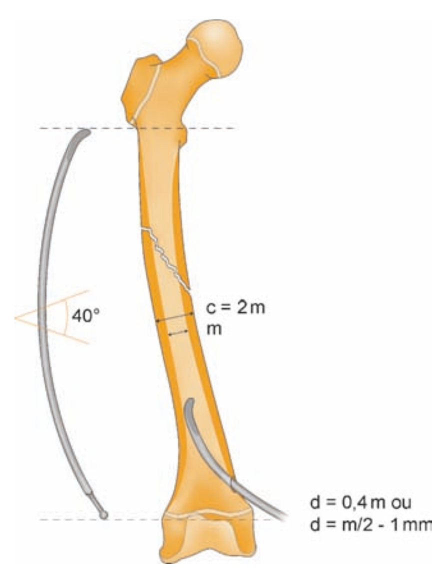


Fig. 18.3 Nail diameter: $d = 0, 4 \times m$ or $d = m/2\text{-}1$. Determination of the length of tapered nails

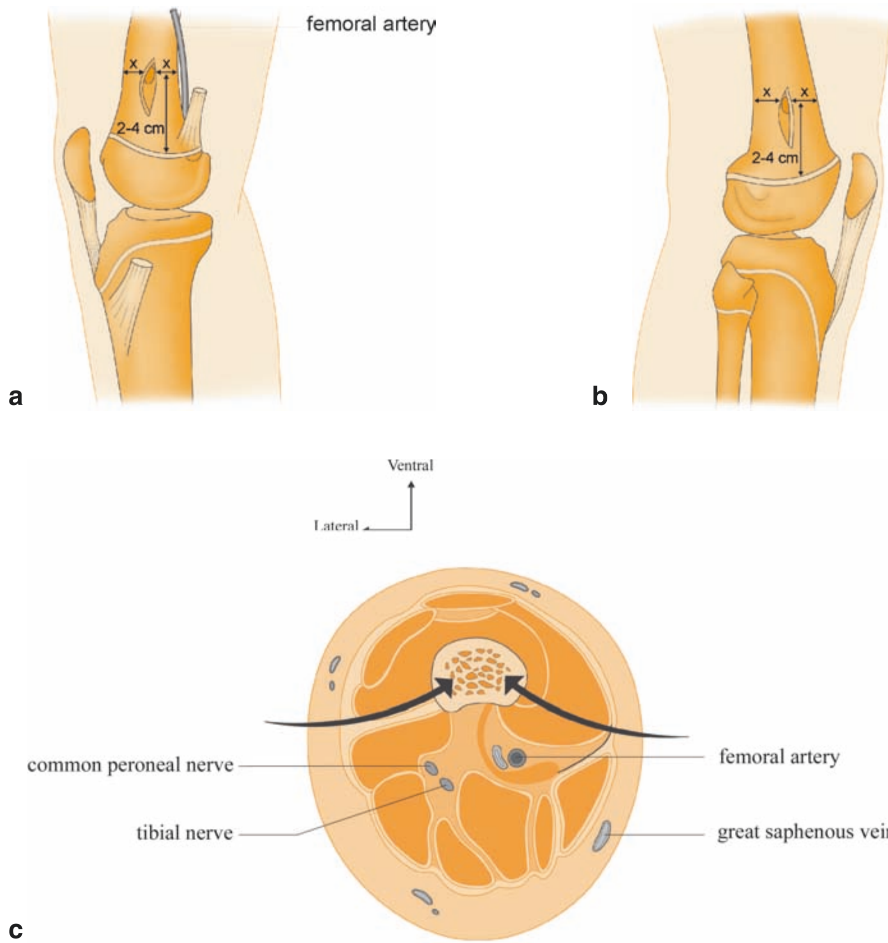


Fig. 18.4 Medial approach to the distal femur: the hole is made 20–40 mm proximal to the physis. The femoral artery lies posterior to the adductor tubercle (**a**). Lateral approach to the distal femur: the hole is made 20–40 mm proximal to the physis. The common peroneal nerve is located far posteriorly (**b**). Anatomic section of the distal femur showing the medial and lateral approaches through the vastus muscles (**c**)

avoid skin impingement during insertion of the nails. The medial entry point is located midway between the anterior and posterior border of the femur, approximately 20–40 mm above the distal physis. It is positioned anterior to the adductor tubercle and anterior to the femoral artery. The lateral entry point is symmetrically located on the lateral aspect of the femur. Therefore, both entry points are away from the physis and positioned deep enough to the skin surface to avoid prominence of the nail ends. Blunt scissors dissection is performed down to the bone surface, taking care to avoid damage to the great saphenous vein that runs medially. After preliminary bone scraping, a hole is created with the awl in the midline (in the sagittal plane), taking care not to let the awl slip posteriorly. The surgeon should not hesitate to make a hole larger than the diameter of the nail, and direct the awl toward the diaphysis to facilitate nail insertion (Fig. 18.5).

The nail is inserted into cancellous bone and advanced up the medullary canal (Fig. 18.6). It is initially introduced perpendicular to the entry hole and then immediately rotated 180° so that its concave side faces the entry point and its leading end does not catch on the opposite wall. Then, the nail can be safely advanced upwards. Using quick oscillary rotary motions are effective in preventing the nail from getting stuck in the bone. Should it happen, better withdraw the nail a little, change direction and resume advancement. The inserter must be firmly tightened at a short distance from the femur to avoid twisting of the nail. The nail should be pushed up to the fracture site using light hammer blows, if necessary (particularly in adolescents), being careful to avoid cortical penetration. As previously mentioned, during progression upwards, it may be useful to sequentially bend the nail as described above (Fig. 18.7).

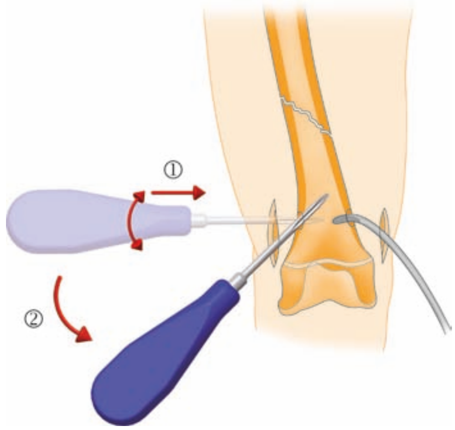


Fig. 18.5 The entry hole is created with an awl at the proximal end of the skin incision. The awl is introduced perpendicular to the entry point and then tilted downwards and point toward the diaphysis

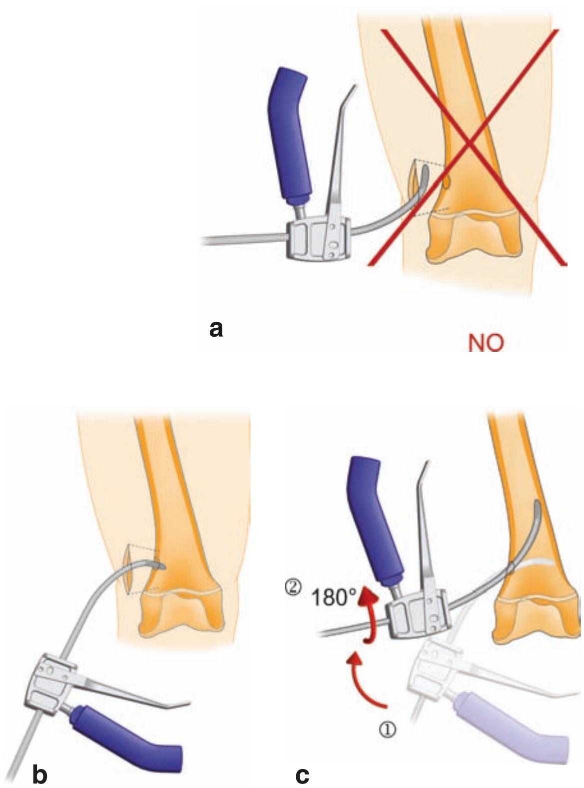


Fig. 18.6 At insertion, the leading end of the nail should not be parallel to the bone surface (**a**); it should be positioned at 90° (**b**). Immediately after insertion, it should be rotated 180° and advanced up the medullary canal (**c**)

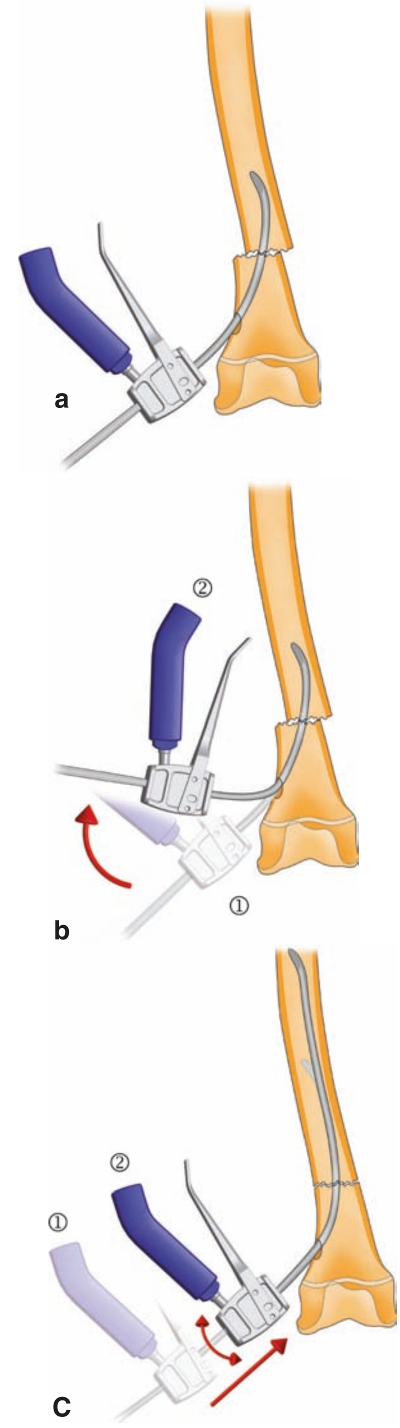
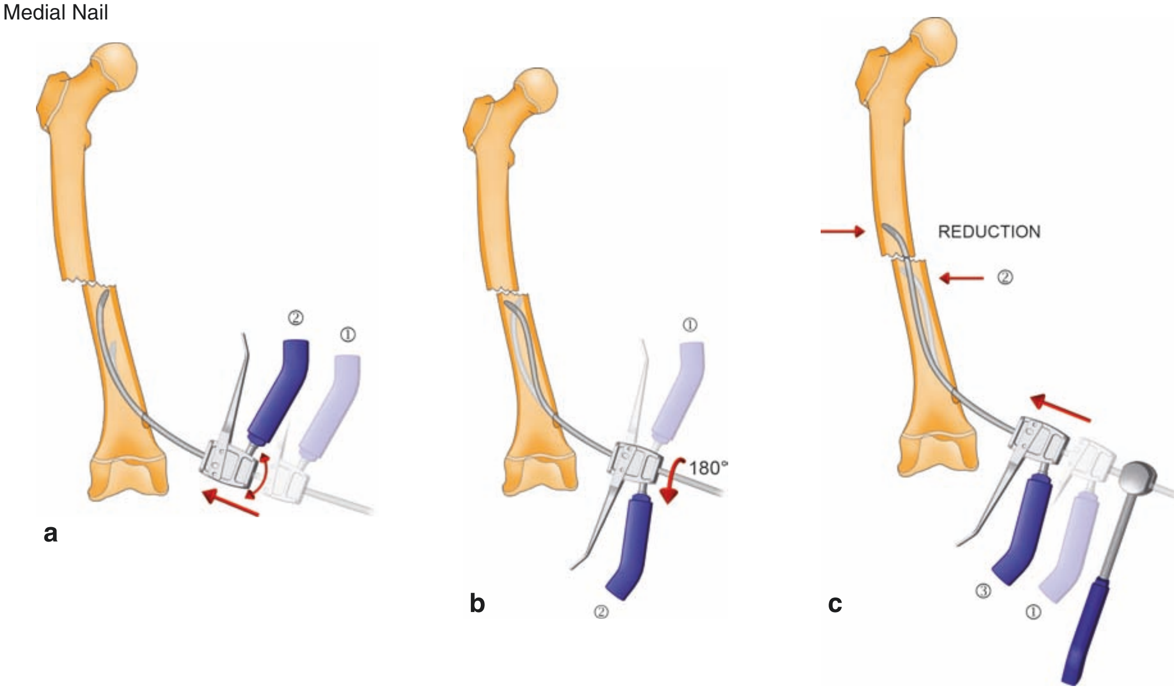


Fig. 18.7 The nail is forced against the opposite wall. If the fracture is very low, the maximum of the curve should be located in the distal region. However, the surgeon should still be able to attach the T-handle. The portion of the nail that is outside the bone is almost straight (**a**). It is then possible to force the nail against the opposite wall to bend it (**b**) and then sequentially advance it upwards (**c**) by repeating the maneuver

Medial Nail



Option One

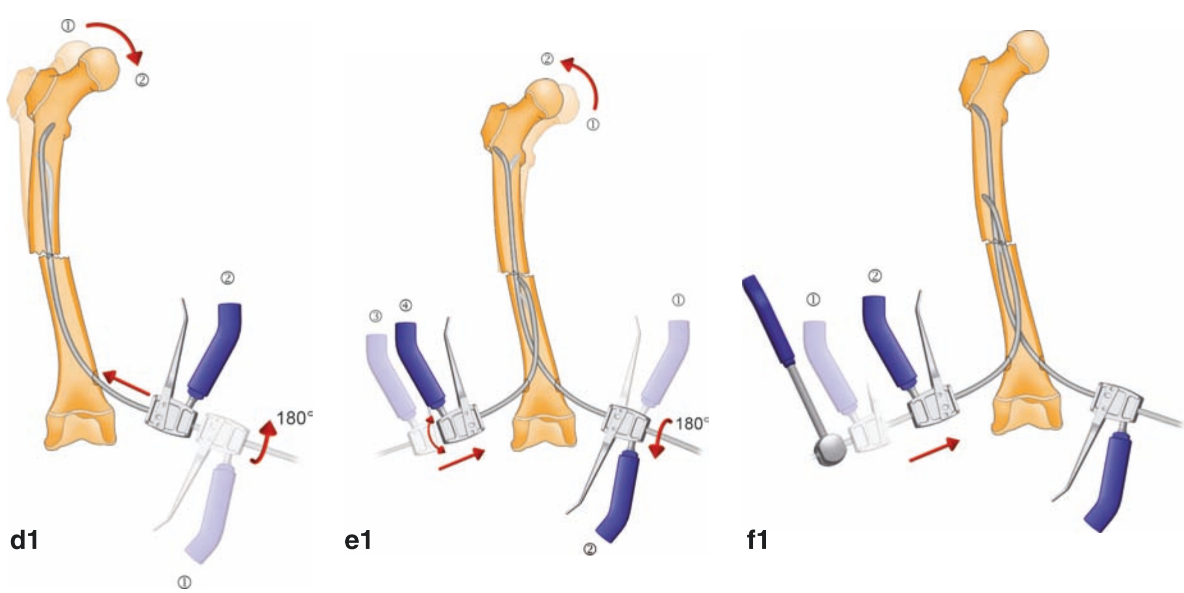
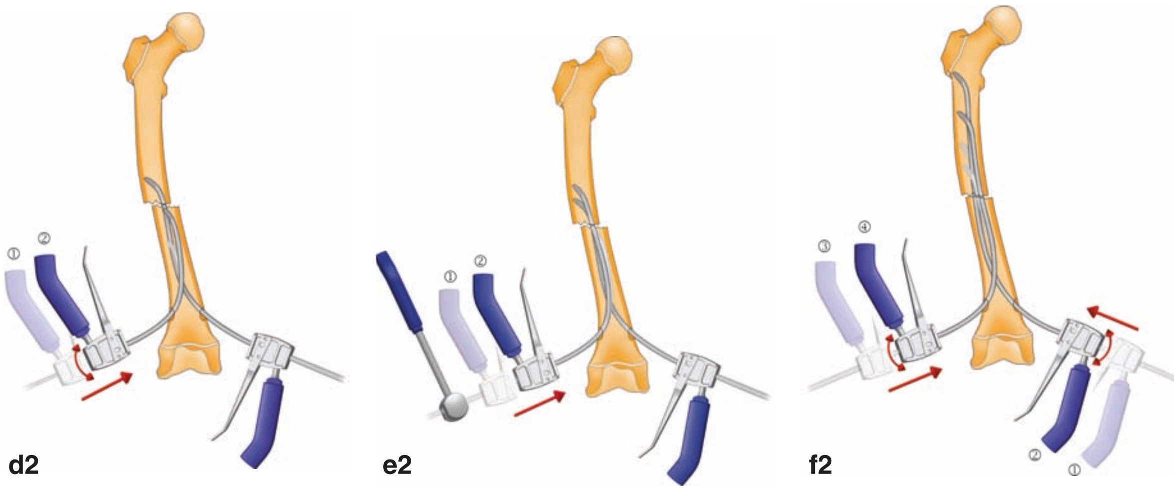


Fig. 18.8 Once the nail has reached the fracture site (**a**), it is rotated 180° so that its tip points toward the opposite bone fragment (**b**). While the fracture is being reduced by external maneuvers, the nail is pushed across the fracture site using a slotted hammer (**c**). At this stage, two options are available: option 1: first nail is advanced up the proximal fragment. But due to contouring, it will cause the femur to shift into a varus position (**d1**). Rotation of the nail changes the position of the distal fragment, thus making it easier for the second nail to cross the fracture site (**e1**). Once it has entered the proximal fragment (**f1**), it is opposed to the first nail which is then rotated to complete the reduction (**g**) (see next page)

Option Two



Final Step

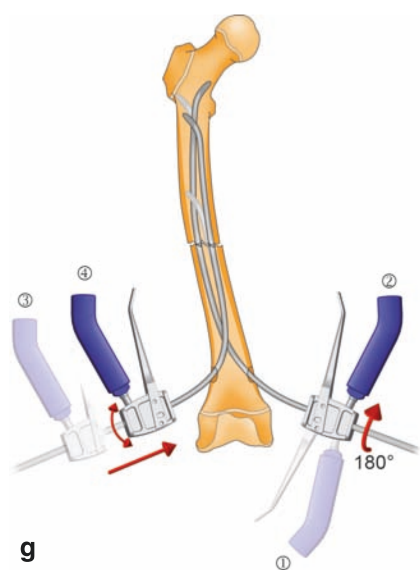


Fig. 18.8 (*cont.*) option 2: taking advantage of the reduction force exerted by the first nail, the second nail is advanced up to the fracture site (**d2**), pushed into the opposite fragment using a slotted hammer (**e2**) and then advanced up the proximal fragment. The first nail is in turn advanced upwards (**f2**). As in option 1, the first nail is rotated to complete the reduction (**g**)

The second nail can be inserted using the same technique, and advanced symmetrically as far as the fracture site.

18.2.8 Crossing the Fracture Site

The nail should be pushed across the fracture site (Fig. 18.8) with the help of a slotted hammer. With hand pushing, the nail may be misdirected toward soft tissue.

It is important to visualize the nail path (both AP and lateral) using fluoroscopy to properly orient its tip for an easy crossing of the fracture site. It is essential to achieve optimal reduction. Once the nail has entered the opposite fragment, it can be advanced further by hand. One option is to insert the first nail, cross the fracture site, advance the nail up to its final position, and then repeat the procedure for the second nail. Another option is to bring both nails to the level of the fracture site, but fluoroscopic images are more confusing and the nails may become entangled. Where anatomic reduction cannot be achieved prior to nail insertion, the curved tip of the nail can assist in engaging the opposite medullary canal, but it is crucial that fracture be disimpacted.

Progression of the second nail is a little bit more difficult due to the presence of the first nail within the canal, but the procedure is exactly the same. The thing is to avoid nail entanglement, which means that the nail must not be rotated more than 180° in either direction. Let's assume that it has been previously rotated 130° clockwise and that the surgeon wants to rotate it 210°. He/she will have to go back (counterclockwise) to the start point and rotate the nail 150° counterclockwise (360° 210° > 150°). In theory, to achieve a stable construct, one must have two nails with opposing curves. But the forces that apply to the construct must be taken into account. Therefore, the nails should be positioned in a way to achieve both adequate reduction and maximum stability [5, 6].

18.2.9 Final Reduction

After the fracture site has been crossed, the nails are advanced by hand as far proximally as possible and are anchored in the metaphysis. Prior to impaction, axial traction should be relieved. Reduction is assessed and if

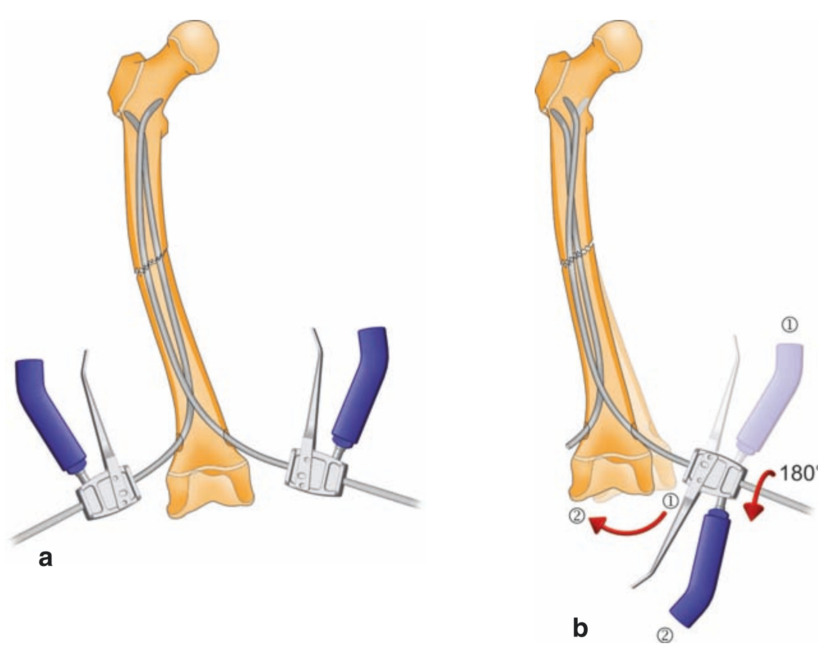


Fig. 18.9 If a slight varus angulation exists with the final construct in place (**a**), it can be corrected by rotating the medial nail 180° (**b**)

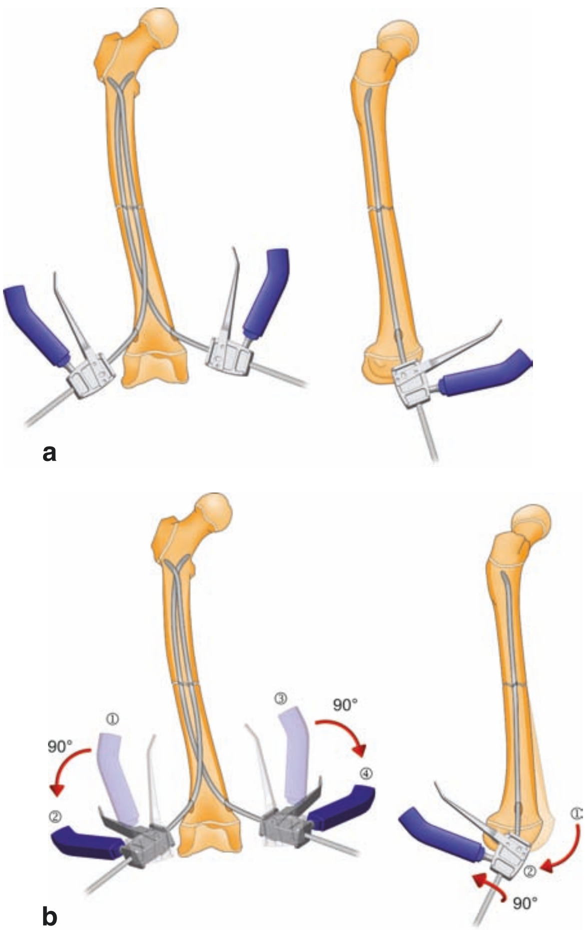


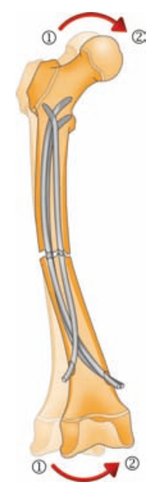
Fig. 18.10 If a slight recurvatum angulation exists with the final construct in place (**a**), it can be corrected by rotating both nails 90° so that their concave sides face posteriorly. Frontal plane orientation remains unchanged (**b**)

inadequate, the position of the nails is adjusted accordingly. In most cases, both concavities will face each other with their apexes located at the fracture site.

Nail contouring may prove very useful to complete reduction of a fracture where mild displacement persists: a slight valgus angulation can be corrected by rotating the lateral nail 180° with its tip pointing medially, and a slight varus angulation can be corrected by rotating the medial nail laterally (Fig. 18.9). In the sagittal plane, a flexion angulation can be corrected by directing both nail tips anteriorly without changing their medial and lateral orientation: this is achieved by rotating the nails only 90°.

Conversely, a recurvatum angulation can be corrected by directing both nail tips posteriorly (Fig. 18.10).

Fig. 18.11 Asymmetric malaligned construct to be used only in case of persistent valgus angulation after a standard FIN: *1* nail directed laterally, and *2* nails directed medially to produce the necessary varus shift



If anatomic reduction is achieved via nail orientation, the nail tips should be pushed into the metaphysis with the help of a slotted hammer. This allows to get a good purchase in the cancellous bone and avoids destruction of bone trabeculae with rotary motions. Then comes final impaction of the fracture site.

In rare cases where severe instability persists after standard FIN, a third nail can be used to achieve a tripod construct. The insertion procedure is exactly the same. The role of this third nail is to counter the destabilizing force (Fig. 18.11).

18.2.10 Wound Closure

The trailing ends can be cut. It is not recommended to bend them too sharply before cutting as they may

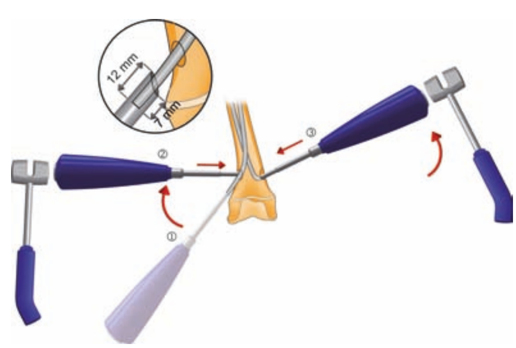


Fig. 18.12 Position of the nail ends after cutting. Nails ends are pushed against the cortical walls using cannulated impactors (*1*). Then, they may be bent 45° (*2*). Alternatively, they may be sharply bent and recessed using a solid impactor and a slotted hammer (*3*)

impinge upon the vastus muscles and cause severe discomfort. Actually, the surgeon should use the elastic properties of the nails (particularly, titanium nails), mildly bend the distal ends and cut them beneath the skin. Once trimmed, the nail ends will spring back and lie flush against the bone. This offers two advantages: no patient discomfort; sufficient nail length is left for later removal. Actually, several options are available to avoid both "too long" nail ends, which cause discomfort and "too short" nail ends, which make removal difficult. The length of the nail tip is determined by the surgeon, taking into account the thickness of the soft tissue and the necessity of later removal. In this respect, the 7–12 mm cannulated impactor has proved, indeed, very useful for final impaction (Fig. 18.12). In certain circumstances, the nails are overbent and recessed into the bone; the aim is to get a strong anchorage distally to avoid any risk of migration (Chap. 5, Fig. 5.16).

The wounds are copiously irrigated and closed in two layers. A compressive dressing is applied. We routinely use surgical glue for skin closure, which obviates the need for postoperative scar care.

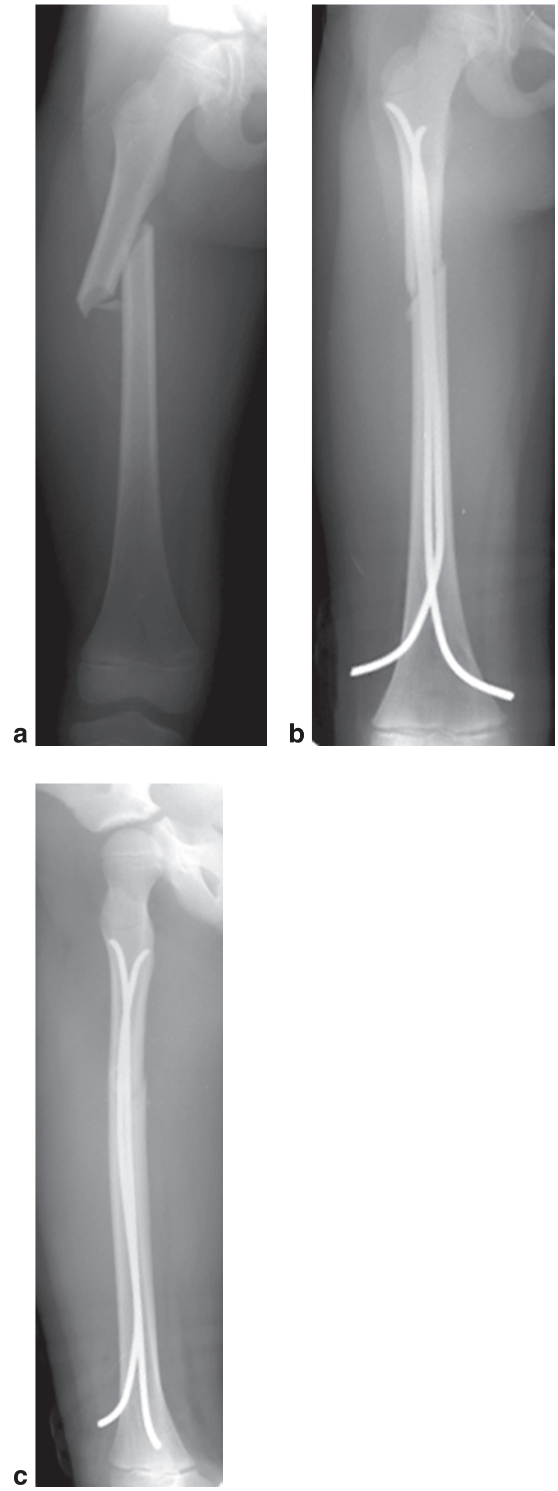


Fig. 18.14 A 9-year-old boy with a fracture at the middle-proximal third junction of the *right femur* sustained during a fall down the stairs (**a**). He was treated with FIN using two 4 mm Titanium nails. Postoperative X-rays: AP (**b**) and lateral (**c**)

18.2.11 Types of Femoral Fractures

18.2.11.1 According to Anatomic Location

Proximal Third

Proximal-third fractures are managed with standard bipolar retrograde FIN. The distal entry points are

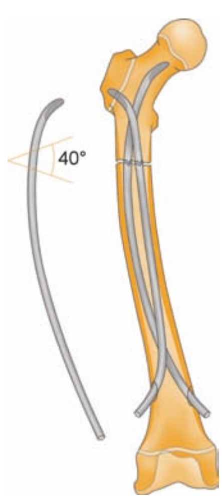


Fig. 18.13 Nail contouring. Two nails with opposing curves are inserted. At the end of the procedure, the apex of the curve (approximately 40°) should be located at the fracture site (proximal third)

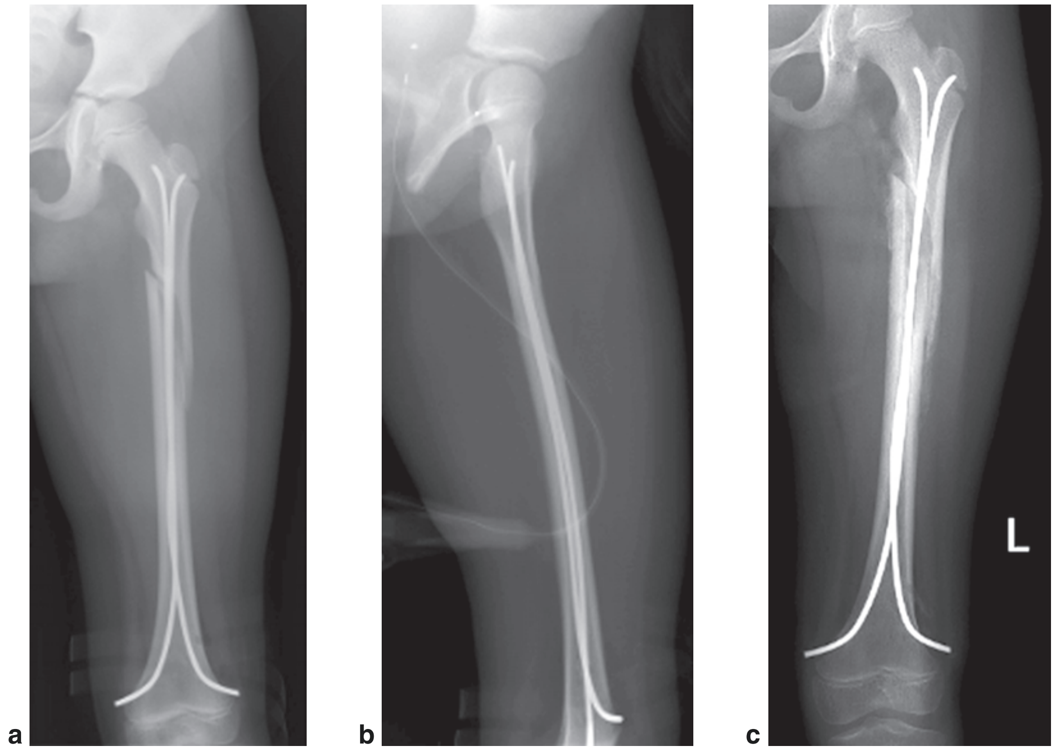


Fig. 18.15 A 7-year-old girl who suffered multiple injuries during a car accident (*left humeral* shaft fracture, *left radial* shaft fracture, supracondylar fracture of the *left humerus*, *left pulmonary* contusion). The spiral fracture of the *left femur* is located at the middle-proximal third junction. The young girl was treated with retrograde FIN using two 2.5 mm stainless steel nails (**a**, **b**). At 6 weeks, there was obvious callus formation (**c**)

usually positioned 50–60 mm proximal to the physis so as to avoid impingement upon subcutaneous tissue or muscles. The patient should be positioned with the knee in 10–15° of external rotation to avoid lateral rotation of the proximal fragment. Ideally, once the fracture site has been crossed, one nail is pushed toward the femoral neck and the other nail toward the greater trochanter (Figs. 18.13–18.15) [7].

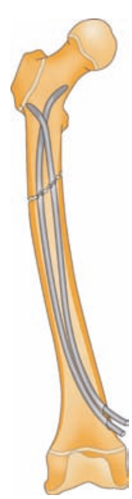


Fig. 18.16 A variant of a medial unipolar retrograde FIN for treatment of a proximal-third fracture

In rare cases, only unipolar retrograde FIN may be considered in a young child. Its advantage is the single distal incision that is usually made on the medial aspect of the femur. Technically, placing a nail with its concave side facing medially is quite easy, but rotating the second nail so that its concave side should face laterally at the fracture site requires a certain amount of skill and experience (Fig. 18.16). The technique is similar to that of unipolar antegrade FIN that is performed in some distal fractures.

Middle Third

Bipolar retrograde FIN is typically the choice for this type of fracture, with the distal entry points positioned approximately 30–40 mm proximal to the physis. Selection of the appropriate diameter and precise

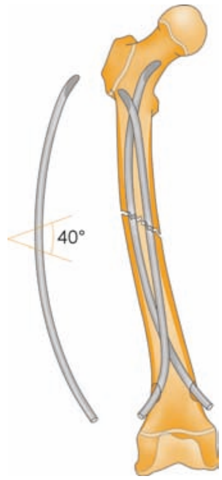


Fig. 18.17 Nail contouring. Two nails with opposing curves are inserted. At the end of the procedure, the apexes of the curves (approximately 40°) should be located at the fracture site (middle third)

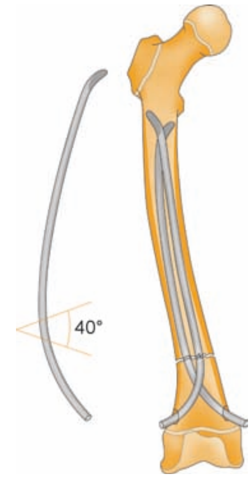


Fig. 18.19 Nail contouring. Two nails with opposing curves are inserted. At the end of the procedure, the apexes of the curves (approximately 40°) should be located at the fracture site (distal third)

Fig. 18.18 A 9-year-old boy run over by a car: craniofacial trauma, *left mandibular* condyle fracture, mid-shaft transverse fracture. He was treated with FIN using two 3.5 mm titanium nails. Note callus formation at 1 month (**a**, **b**)

Fig. 18.20 A 9-year-old boy with a transverse femoral fracture at the middle-distal third junction sustained during a fall from an attic (2.50 m) (**a**)

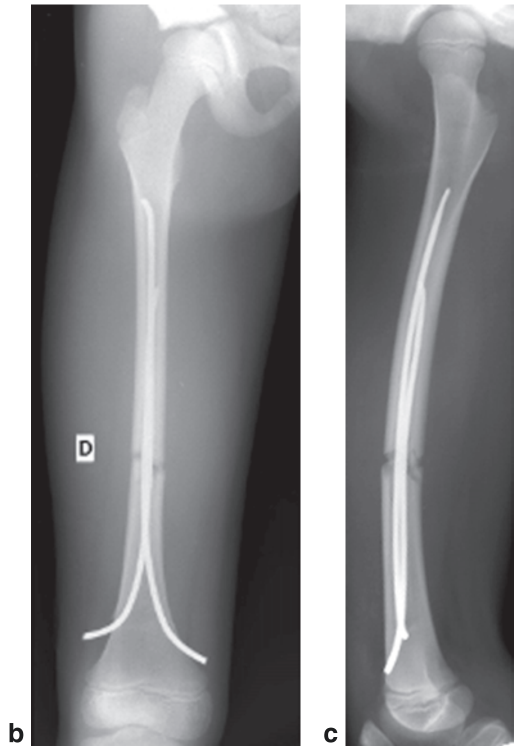


Fig. 18.20 (*cont.*) Retrograde FIN using two 3.5 mm titanium nails with a short proximal section (**b**, **c**)

contouring are critically important. These fractures are a problem in adolescents, especially in overweight children where 4 mm stainless steel (stiffer than titanium alloy) nails should be preferred. Large medullary canals may accommodate four nails. The nails are advanced as far as the subtrochanteric region, without attempting to reach the femoral neck. As a matter of fact, blunt-tipped nails do not easily enter the dense cancellous bone, and forceful advancement might result in distraction of the fracture site, and eventually in limb lengthening in the case of a transverse fracture (Figs. 18.17 and 18.18). A tapered tip will easily penetrate dense cancellous bone.

Distal Third

Two options are available, depending on the type of fracture:

- Retrograde FIN -A technically difficult procedure for two reasons: distal position of the entry points with the nail ends lying beneath the skin; difficulty in getting the nails to cross each other distal to the fracture site. The surgeon should not hesitate to force

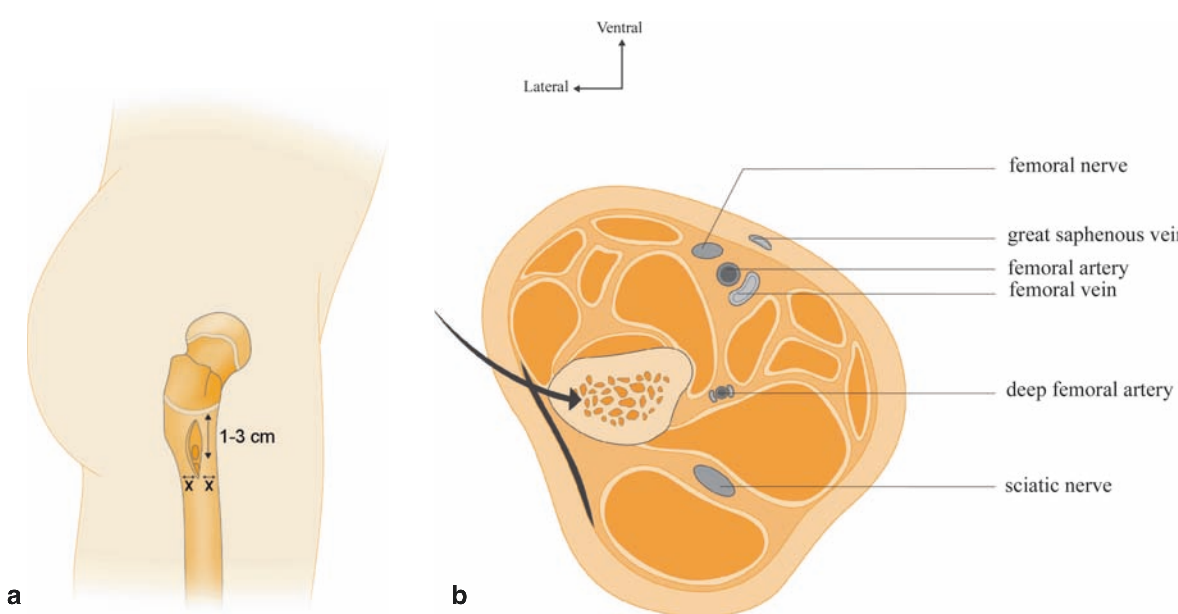


Fig. 18.21 Lateral subtrochanteric approach. Incision made 10–30 mm below the physis (**a**). Anatomic section of the proximal femur (**b**)

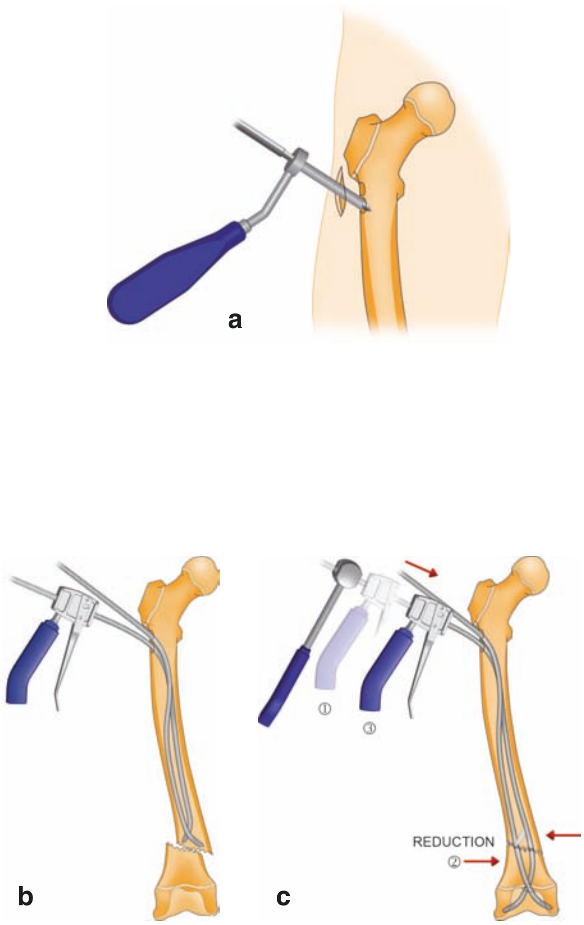


Fig. 18.22 Antegrade FIN: entry hole is drilled (**a**). The first nail is advanced alongside the lateral cortex down to the fracture line. The second nail is rotated right after insertion into the femur and directed medially (**b**). The fracture is reduced and both nails are pushed across the fracture site with the help of a slotted hammer. Reduction is maintained while the first nail is directed toward the lateral condyle and the second one toward the medial condyle. In very distal fractures, the nails can even pass through the distal physis and end up in the lateral and medial condyles (**c**)

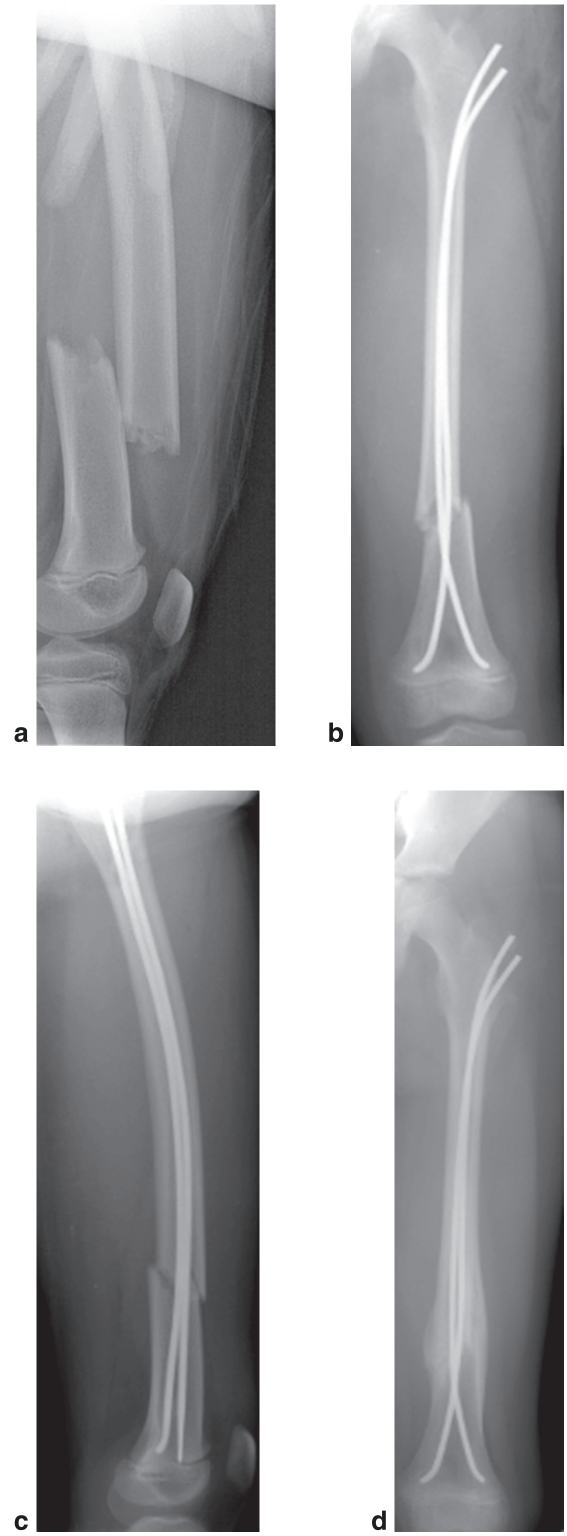


Fig. 18.23 A 7-year-old girl run over by a car sustained a distal-third fracture of the femur (**a**). She was treated with antegrade FIN using two 3.5 mm titanium nails. Postoperative X-ray (**b**, **c**). Bone union achieved at 3 months (**d**)

them against the cortical wall as they progress upwards to achieve an adequate curvature (Figs. 18.19 and 18.20).

- Antegrade FIN [8, 9] – Proximally, the entry point is located below the lesser trochanter, approximately 20 mm distal to the growth plate (Fig. 18.21). In this dense cortical bone, it is recommended to drill two holes, one above the other. The technique is basically the same as that used in metaphyseal fractures (e.g., supracondylar fractures of the elbow) (see Chap. 14), where each nail is directed toward a condyle (medial or lateral). In very distal fractures, the nails can even pass through the distal physis (Figs. 18.22 and 18.23).

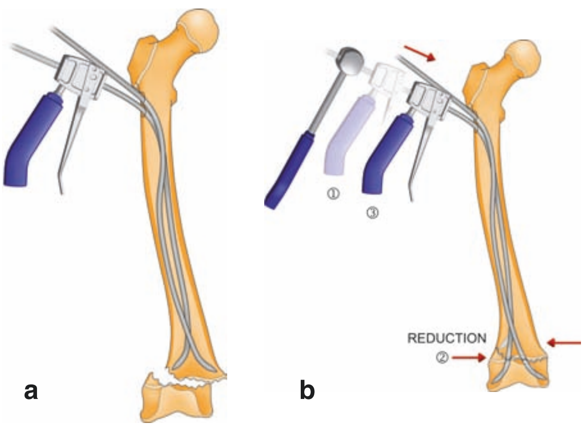


Fig. 18.24 Distal epiphyseal separation in a young child. A subtrochanteric approach is used. Both sharp nails are advanced down to the distal metaphysis, each of them being directed to a femoral condyle (medial or lateral) (**a**). After reduction of the fracture, the nails are pushed into their respective condyles with the help of a slotted hammer (**b**)

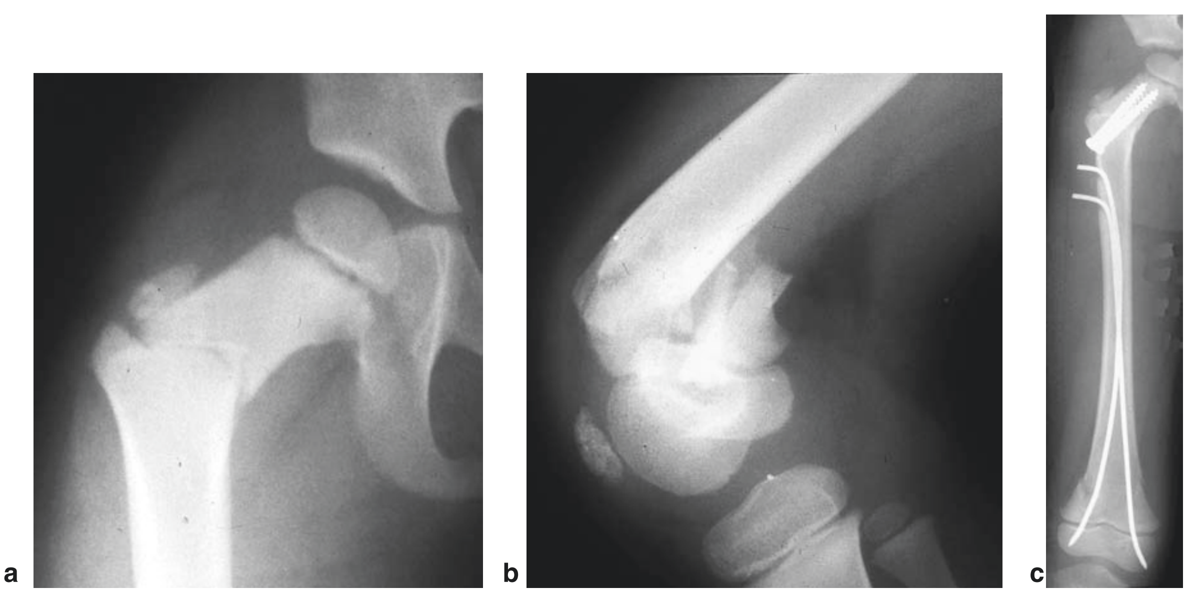


Fig. 18.25 An 8-year-old girl with a wrist fracture and a double femoral fracture (**a**, **b**). The femoral neck fracture was fixed with screws and the distal femoral fracture was managed with antegrade FIN (**c**)

Supracondylar Fracture

Supracondylar fractures are often amenable to simple screw fixation or other internal fixation methods. However, FIN remains a good option, particularly in young children. In this case, the nails must have sharp or slightly tapered tips to engage the distal fragment as in supracondylar fractures of the elbow. Traction is not necessary as reduction can generally be achieved with the knee flexed.

Both nails are gently contoured and gently bent at their leading ends, and advanced down to the fracture site with their tips directed slightly posteriorly in opposite directions. The fracture is reduced and the nails are pushed through the growth plate to end up in each condyle, just short of the articular surface (Figs. 18.24 and 18.25).

Femoral Neck Fractures

Apart from some pathological fractures, femoral neck fractures are usually not amenable to FIN. The reason is that the cancellous bone is so dense that nail insertion tends to cause distraction of the fracture site, and stabilization is much more difficult to achieve than with conventional screw systems (Case 1).

Fig. 18.26 A 14-year-old boy weighing 98 kg presented with a transverse femoral fracture sustained during long jumping activity, due to bad landing (**a**). He was treated with bipolar retrograde FIN using two Nancy®-type 4 mm titanium nails. Owing to adequate reduction and perfect construct, the fracture healed uneventfully (**b**, **c**). Radiograph at 1-year follow-up (**d**)

18.2.11.2 According to Fracture Pattern

Transverse or Short Oblique Fractures

In transverse or short oblique fractures, an experienced surgeon will not have difficulty in pushing the curved tip of the nail across the fracture site. Even borderline cases like the obese patient (98 kg) whose radiograph is shown in Fig. 18.26 can be managed with FIN.

Long Spiral or Comminuted Fractures

Long spiral or comminuted fractures are a little more challenging. FIN is best performed with the use of two image intensifiers, which allow full control of nail advancement and gradual rotation to follow the spiral path, or progression through the comminution zone. A perfect construct is mandatory to stabilize these fractures.

18.2.12 Postoperative Care

AP and lateral X-rays are required. The lower limb is elevated, a pillow is placed under the thigh for a few days, and a sand bag may be used to stabilize the foot and prevent external rotation. A simple dressing is applied and replaced on the second postoperative day.

Physical therapy helps hasten recovery of the quadriceps strength and active contraction. Active mobilization of the knee and foot is also recommended; the child is instructed and encouraged to lift the leg off the bed. As soon as he/she can, the child gets out of bed and begins to walk with two crutches, being careful to put no weight on the injured leg. Once the child has regained a certain level of functional independence, he/she is discharged from hospital and returns home. The length of hospital stay is only 1 week (maximum).

Both the child and the family are informed that subcutaneous prominence of the nails is absolutely normal and will disappear as soon as the nails are removed. Once the wound has healed, the child is requested to gently mobilize the skin area around the cut ends of the nails to prevent tissue adhesion.

18.2.13 Medical Treatment

Pain killers associated or not with antiinflammatories are prescribed until complete resolution of pain. DVT prophylaxis (low-molecular weight heparin: LMWH) is routinely used in adolescents until full weight bearing is resumed.

18.2.14 Rehabilitation

As reduction and stability are always very satisfactory, postoperative immobilization is unnecessary. Physical therapy helps hasten recovery of functional independence. It should be focused on active quadriceps exercises and achievement of knee locking in extension. As regards flexion, only gentle exercises are performed due to the painful prominence of nail tips. Besides, the child will recover full range of motion in the knee after removal of hardware.

18.2.15 Resumption of Activities

The child returns to school within 1–2 weeks after discharge, as long as he/she is able to walk with two crutches.

Time to weight bearing is relatively short: approximately 2–3 weeks for transverse fractures, and around the sixth week for long spiral and oblique fractures and comminuted fractures.

At 2 months, the child should have a good ambulatory status and is able to evaluate his/her ability to resume gentle physical activities like swimming. At 4 months, the child can return to individual sports. Clinical and radiological follow-ups are scheduled at 3 weeks, 6 weeks and 3 months postoperatively. Once union is complete, hardware removal can be considered.

18.2.16 Implant Removal

The nails can be removed under general anesthesia as soon as union is achieved, that is, from the fourth postoperative month, sometimes earlier. Titanium nails promote bone ongrowth so that removal of such nails after a prolonged implantation period (i.e., 1 year) may be somewhat difficult. The dedicated instrument system includes locking forceps that may be used in combination with a slotted hammer to facilitate removal of the nails. This is most helpful with 3.5 or 4.0 mm nails, particularly where the medial nail has been cut flush with the bone surface.

The procedure can be performed on a day-patient basis using the previous scars. Immediate weight bearing is allowed, but the child is requested to refrain from high-impact and collective sports for 2 months to reduce the risk of fracture at the hole sites.

18.2.17 Postoperative Follow-Up

Depending on the age of the child and the presence or absence of residual angulation or other complications, a radiographic assessment is routinely performed at 1 year and at 2 years, based on full-length X-rays of the lower limbs in standing position to check for correct alignment and leg length equality. A child with an excellent outcome does not need further follow-up and is considered (legally) as permanently healed.

In the presence of leg length discrepancy or malunion, longer clinical and radiological follow-up is required.

18.3 Complications [4, 10–12]

18.3.1 Difficult Reduction

If the patient is positioned on a fracture table and a correct amount of traction is applied, reduction is generally easy to achieve. Even if the bone fragments are not perfectly aligned, a well guided nail will easily cross the fracture site with the help of gentle external maneuvers. However, open surgery is sometimes necessary, particularly in distal-third fractures or in fractures with a long third fragment where it is just impossible to perform adequate contouring of the nail to cross the fracture site. In this case, a short incision is sufficient to reduce the fracture and allow crossing of the fracture site under visual control. Alternatively, percutaneous reduction can be achieved using a punch to push the bone.

18.3.2 Nail Misdirection

If a large hole has been created with the awl, the risk of misdirecting the nail at insertion is very low. By using the nail as a probe to feel the bone, misdirection is immediately detected and corrected.

When crossing the fracture site, the surgeon should always check the nail path on AP and true lateral

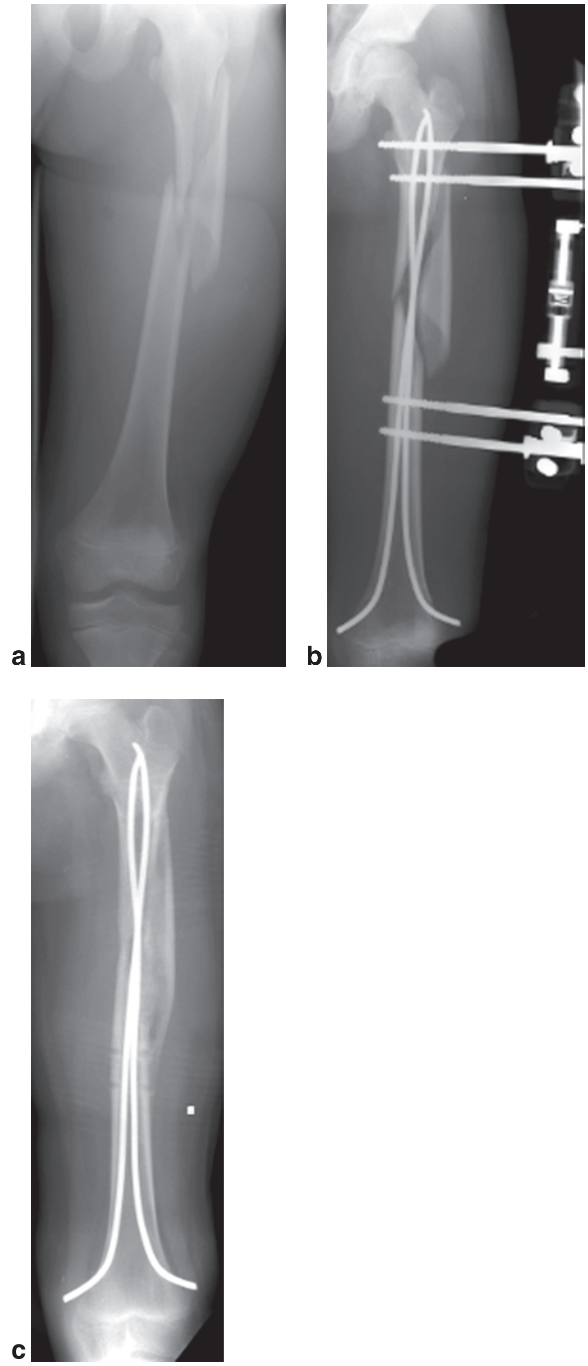


Fig. 18.27 A 12-year-old boy with a spiral fracture of the *left femur* and a third fragment located at the proximal third of the diaphysis sustained during a mountain bike accident (**a**). He was treated with retrograde FIN using two 4 mm stainless steel nails and, as leg length failed to be restored, FIN was immediately associated with an external fixator. X-ray taken on the 15th postoperative day (**b**). Fixator removed 3 months later. Nails to be removed at 8 months (**c**)

X-rays (90° angle between both views). It is in comminuted or long spiral fractures that the risk of misdirecting the nail into soft tissue is highest. In this case, the fracture site must be crossed very slowly using gentle hammer blows under fluoroscopic guidance.

18.3.3 Instability

There are a few important points to remember:

- Implants: Always use the largest diameter that can be accommodated. Do not hesitate to use stainless steel nails in middle-third fractures.
- Technique: Nail contouring is a critical step. Achieving the ideal curvature is a matter of experience. In case of problem, do not hesitate to remove the nail and insert a new one.
- Fracture pattern: Comminuted or long spiral fractures are more unstable and require a perfect construct.

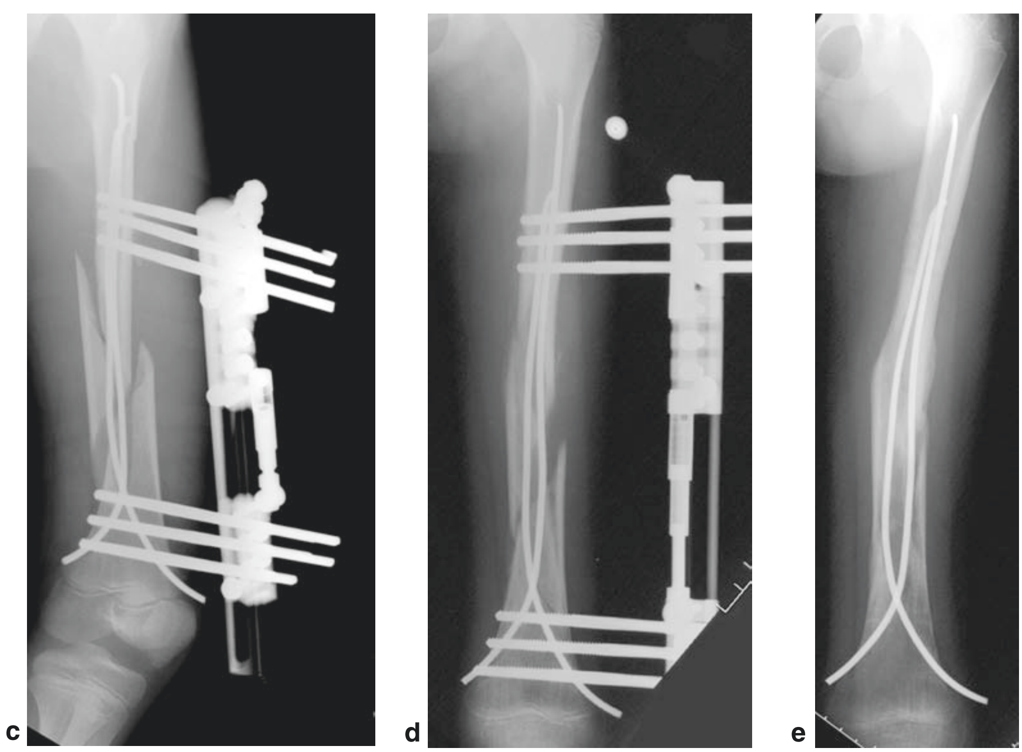


Fig. 18.28 A 9-year-old boy with a spiral fracture (and a large third fragment) at the middle-distal third junction of the *left femur* sustained during a fall from a tree (**a**). Emergency retrograde FIN was performed using two 3.5 mm titanium nails (**b**). Postoperative impaction of the fracture site and 50 mm leg shortening required immediate application of an external fixator to achieve gradual lengthening (**c**). Leg length was restored in 1 month (**d**); external fixator was removed at 3 months. There is a residual valgus angulation of 8° (**e**)

If there is a residual instability in an adolescent who is too young to receive an intramedullary locked nail, FIN may be used in association with an external fixator as a last resort. The external fixator will provide a stable reduction with correct leg length pending initiation of callus formation . The fixator will be left for a period of 4–6 weeks after which nails alone are sufficient until completion of the healing process (Fig. 18.27).

18.3.4 Secondary Displacement

As FIN is performed in recumbent position or using traction, there is always a risk of secondary displacement. We wish to emphasize the importance of final impaction of the fracture site and nails at end of the procedure for optimal stabilization. A secondary displacement may require revision of the construct by simply changing the direction of one of the nails or replacing it (Case 2). Adjunctive cast immobilization may be used but with very little success in the femur as compared to the tibia. The use of an external fixator may be a salvage option (Fig. 18.28). However, it should be pointed out that secondary displacement is most often due to a faulty technique. Nail undersizing is the most frequent mistake (Case 3).

18.3.5 Implant-Related Problems

The most common implant-related problem is skin impingement. Nail tips that are in a very distal position should not be bent. They just need to be moved away from the bone surface for trimming and then allowed to spring back (owing to their elastic properties) and lie flush against the bone. As a matter of fact, with the entry points located at the distal metaphyseal-diaphyseal junction, the nail tips lie next to the femoral condyles. Very often, they must be recessed using the impactor and left only 7–12 mm proud of the bone surface. In case of early impingement, recutting the nail tips may be sufficient (Fig. 18.29).

Fig. 18.29 View showing appearance of the skin just before nail breaks through

18.3.6 Joint Stiffness

As long as the surgeon adheres to the surgical technique with respect to entry points and final trimming, there is no reason to fear postoperative joint stiffness. Joint stiffness is often due to impingement of bent tips upon muscles. Where the distal entry point is too low, stiffness may result from penetration of the joint capsule, which causes hemarthrosis. In any case, restriction of flexion is generally transitory and disappears after removal of hardware.

18.3.7 Delayed Union and Nonunion

Delayed union may be seen in patients with a complex fracture resulting from high- energy trauma or with an open fracture. However, weight bearing which is highly encouraged promotes healing and so far, we have not had any nonunion.

18.3.8 Infection

We have had two cases of superficial infection due to nail tip protrusion through the skin. Debridement, some trimming of nail tips, and sometimes appropriate antibiotic therapy are usually effective in curing the infection. Osteomyelitis developed at the entry sites in two patients suffering from CP. Both nails had to be removed and prolonged medical treatment was necessary. We have not experienced any infection at the fracture site, but osteomyelitis of the distal shaft was diagnosed in two patients after removal of hardware and required appropriate treatment: drainage of bone abscess and antibiotics for 3 months (Fig. 18.30). In cases where early removal of the nails is necessary, an external fixator may be used as an alternative.

Fig. 18.30 A 13-year-old boy with a transverse femoral fracture sustained during a scooter accident (**a**). Bilateral retrograde FIN was performed using two 3.5 mm titanium nails. Union took place in 3 months (**b**). One year after the nails had been removed, the child complained of pain of inflammatory origin in the distal femur. Imaging suggested osteomyelitis (**c–e**). Surgical drainage and isolation of staphylococcus meti-S. Antibiotics for 3 months. Infection cured. Radiograph taken at 4 years (**f**)

18.3.9 Vascular Complications

Vascular lesions are mostly seen in double fractures of the lower extremity (femur or tibia) or so-called "floating knee fractures." In case of emergency, immediate fixation of the fracture allows revascularization to take place rapidly. The surgeon has the choice between external fixation and FIN that is performed on a standard operating table (which often requires open reduction).

18.3.10 Compartment Syndrome

A true compartment syndrome may occur in the thigh. We have personally experienced one compartment syndrome during a long, difficult procedure. This requires at least fasciotomy of the anterior compartment of the thigh.

18.3.11 Refracture with Hardware in Situ

A new severe trauma may cause the femur to refracture. The nails get bent, which results in displacement of the bone fragments. We have never experienced implant breakage. Most often, straightening the nails under general anesthesia is sufficient (Cases 4 and 5). However, if this fails, one or both nails must and can be replaced, thus eliminating the need for switching to other devices.

18.3.12 Difficult Implant Removal

Removal of the nails is generally a straightforward procedure as long as the nails have not been left in situ for more than 6 months (particularly titanium nails). The surgeon should remember to leave sufficient nail length at the end of the procedure to facilitate later removal, and to use locking forceps together with a slotted hammer for easy removal of the nails (Chap. 7).

18.3.13 Malunion

The inherent remodeling capacity of the femur is well known and is particularly high in young children. However, this potential has limitations. In children more than 10 years old with rotational malunion resulting from retroversion of the femoral neck (or external rotation of the knee), only minimal correction can be expected (Case 6). In contrast, a flexion and/or recurvatum angulation of 10° is well tolerated. As regards frontal varus or valgus angulation, a gain of 2° per year can be achieved during 3 years (approximately) so that a total correction of up to 6° can be obtained. Considering the degree of physiological variation from one child to another, a surgeon should not select children aged more than 12 years with a frontal angular deviation greater than 5°, and children aged less than 12 years with a frontal angular deviation greater than 8–10°.

18.3.14 Leg Length Discrepancy

Analysis of a study involving 175 isolated femoral fractures [13] showed that eight children had required epiphysiodesis before end of growth for leg length discrepancy of over 20 mm. Five of them had leg length inequality before their accident, and three children aged less than 10 years had transverse fractures. Evaluation of all the children under 10 years of age showed that those with a transverse fracture had a mean lengthening of 8.8 mm, whereas those with spiral and oblique fractures had hardly any leg length discrepancy. In the group of children over 10 years, transverse fractures had resulted in lengthening of only 3.4 mm, whereas spiral or oblique fractures had resulted in shortening of less than 10 mm owing to immediate impaction of the fracture site.

It was concluded that:

- Before 10 years of age, mean bone overgrowth is 8.8 mm and is mainly seen in transverse fractures where fragment overlap is impossible. This is the reason why these fractures must be impacted before inequality gets worse. In contrast, in spiral and oblique fractures where 10 mm shortening is often noted after the procedure, overgrowth readily compensates for initial shortening.

- After 10 years of age, overgrowth significantly decreases to eventually stop around the age of 13–14 years. This explains that transverse fractures have a good prognosis, whereas in other fractures, the initial shortening is not compensated.

In any case, the child should be monitored for excessive overgrowth, while knowing that potential progression is only a few millimeters over a period of 2–3 years and is nil thereafter.

18.4 Indications [14–28]

Since 1979, in our department, almost all children more than 6 years and less than 16 years presenting with a femoral fracture have been treated with FIN.

Indications include:

- Isolated transverse, oblique, spiral (simple or comminuted) fractures; fractures with a third fragment account for 20% of the cases.
- Gustilo Type I and II open fractures.
- Double femoral fractures (Case 2).
- Ipsilateral fractures of the lower limb.
- Fractures with associated traumatic injuries (multiply injured patients).

Before, FIN was preferred to nonoperative treatment in multiply injured children aged 6 years and less [29]. Now, FIN tends to be used in all children aged 5–6 years to reduce the length of hospital stay and allow quicker recovery of functional independence.

18.5 Contraindications and Limitations

Actually, contraindications are related to the limitations of the treatment method and OR team routines:

- Fractures, which occur after closure of the physis of the greater trochanter are considered as adult fractures and should be managed with intramedullary locked nails [30–33].
- Type III open fractures are preferably treated with external fixation after thorough debridement; recently developed pediatric intramedullary locked nails inserted through the greater trochanter have become an alternative to FIN for the treatment of severely unstable fractures in children around 10 years of age.
- In certain floating knee fractures with vascular complications, switching from a standard operating table to a fracture table (and vice versa) and changing patient position would be time-consuming and therefore detrimental to revascularization. In such cases, the use of an external fixator is advisable [34] (Chap. 20).

18.6 Conclusion

In spite of a lower rate of road traffic accidents, femoral fractures in children are still frequent. FIN is the treatment of choice for a child who is too old to be treated by cast immobilization and too young to receive an intramedullary locked nail [35–37].

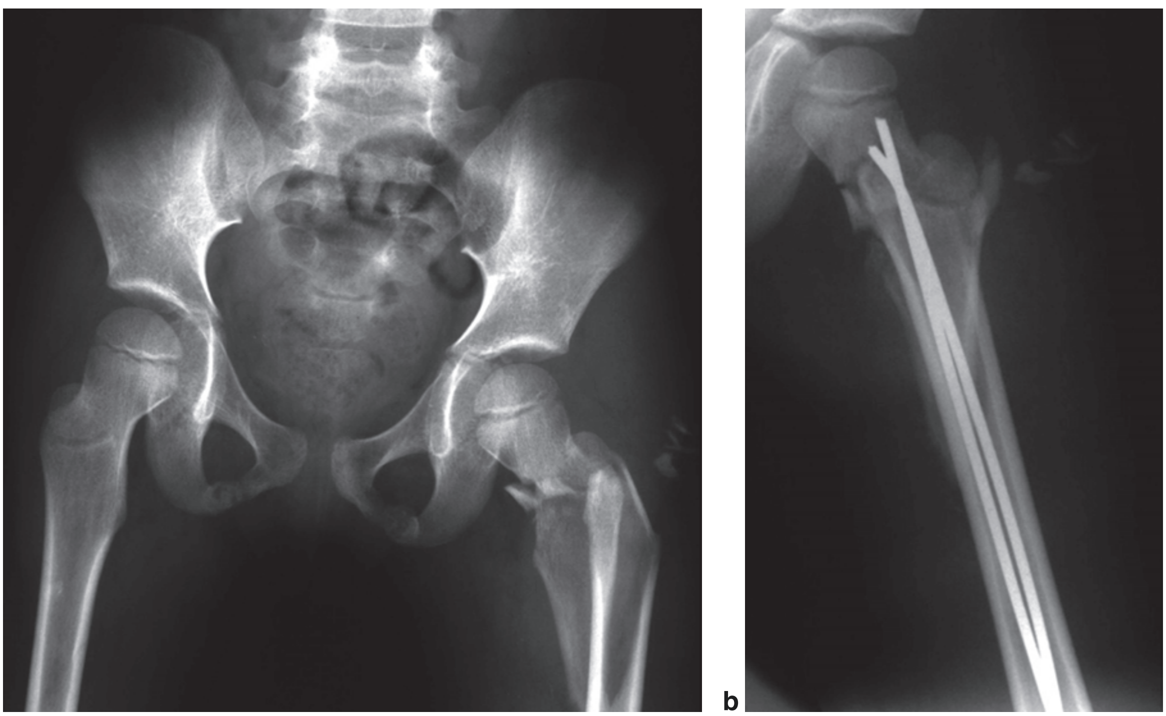
In transverse or simple oblique fractures, FIN is a relatively straightforward procedure, but in long spiral fractures or severely comminuted fractures it can be a real challenge. A skillful and experienced surgeon is able to treat almost all femoral fractures with FIN but in some cases, adjunctive fixation (i.e., external fixator) is temporarily required.

18.7 Case Reports

18.7.1 Case 1

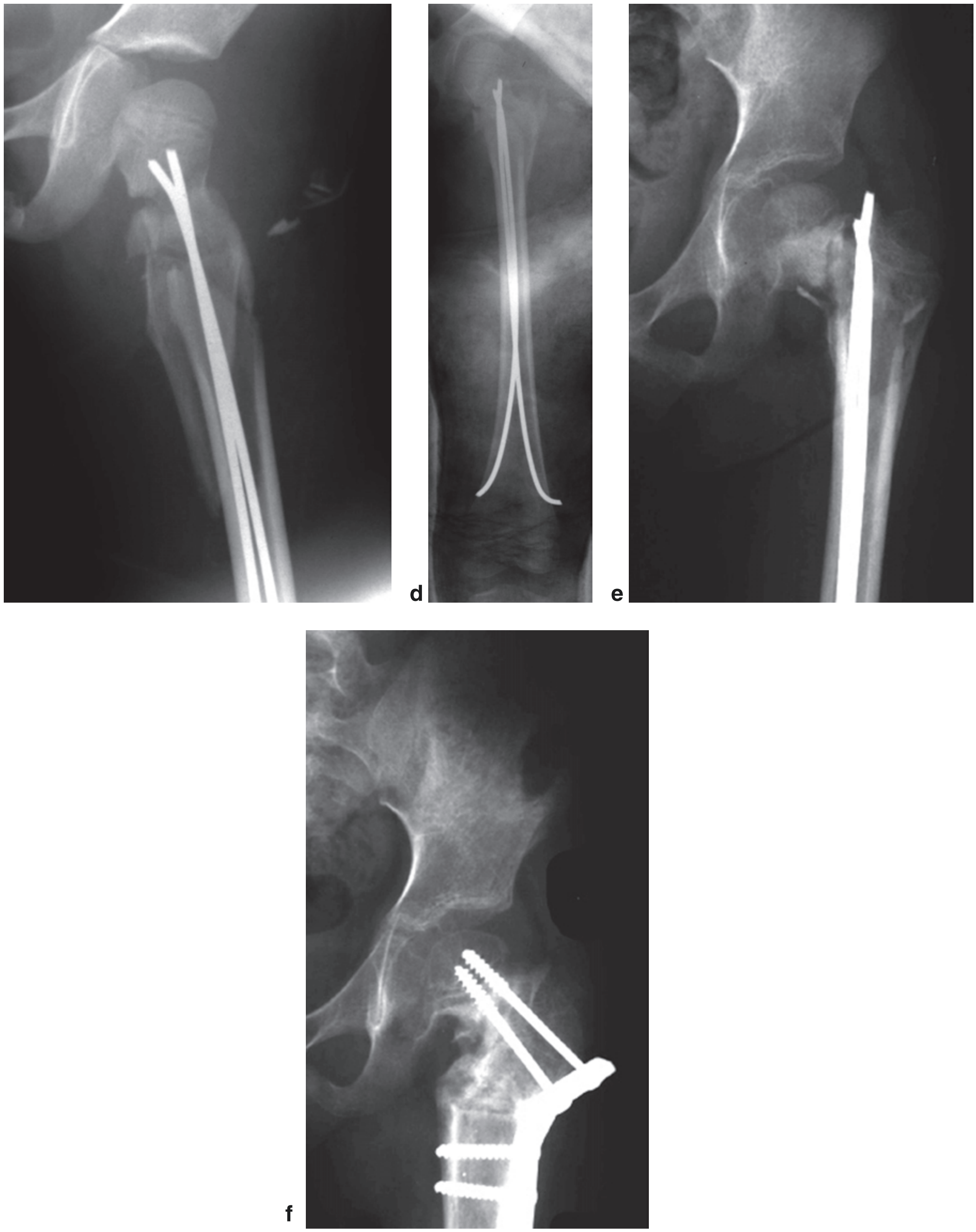
A 6-year-old girl presented on April 15, 1984 with a complex open fracture (Type I) of the left proximal femur with a basal neck component. The injury occurred during a road traffic accident (a). We relied on our experience and familiarity with Ender nails and performed a FIN using 2.5 mm stainless steel nails (b, c) protected by a hip spica cast (d). Secondary displacement of the femoral neck fracture occurred 2 months later, which progressed toward nonunion and coxa vara. The proximal-third fracture was united (e). Nonunion was managed with femoral valgus osteotomy (f) (Fig. 18.31).

Note: Femoral neck fractures in children are not a good indication for FIN.



a b

Fig. 18.31 Case 1



c d e f

Fig. 18.31 (*cont.*) Case 1

18.7.2 Case 2

A 9-year-old girl run over by a car sustained a bilateral femoral fracture (a). An emergency bilateral retrograde FIN was performed using two 3.5 mm stainless steel nails in each femur. A perfect construct was achieved in the right femur, whereas in the left femur the nails crossed each other at the fracture site, which resulted in a varus angulation of 10° (b). The left FIN was revised: one of the nails was replaced and a third nail was inserted and directed laterally to counter the varus forces. At 2 months, the result was satisfactory (c). Union was achieved by 3 months (d–f). At 3 years, axial alignment and leg length were normal in both legs (g) (Fig. 18.32).

Note: the nails crossed each other at the fracture site, which was responsible for the varus angulation.

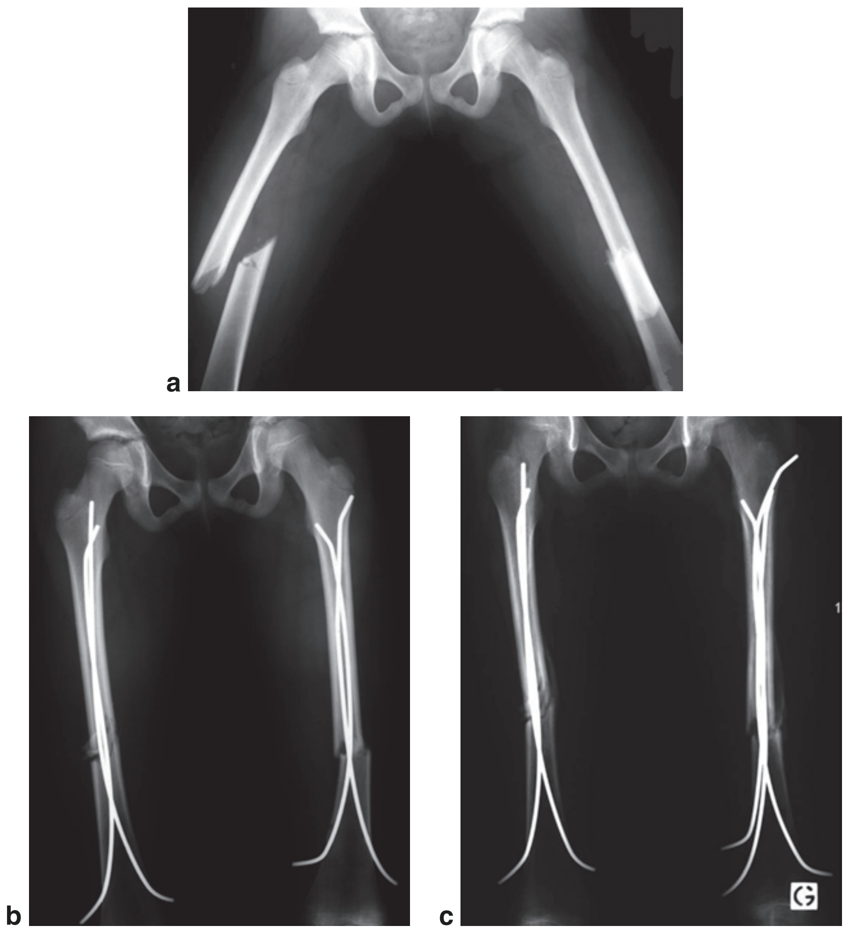


Fig. 18.32 Case 2

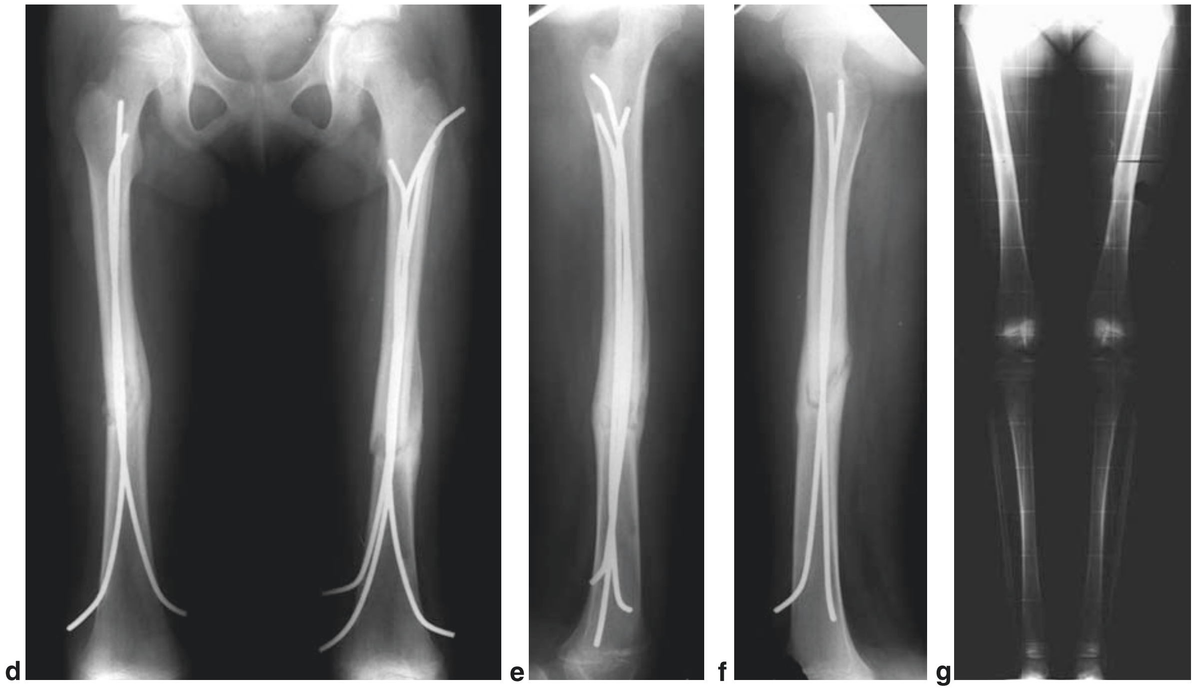


Fig. 18.32 (*cont.*) Case 2

18.7.3 Case 3

A 14-year-old boy with a spiral fracture of the right femur and a third fragment located at the mid-shaft, sustained during a scooter accident as a rear passenger (a). An emergency retrograde FIN was performed using two 3.5 mm titanium nails. The postoperative X-ray showed leg shortening and, more importantly, unacceptable varus angulation of 20° (b). Although there was still an active physis at the greater trochanter, it was decided to remove the FIN construct and replace it with an intramedullary locked nail (c). Six weeks later, the lateral view showed evidence of initial callus formation around the large third fragment (d). Ten months later, the AP view showed union of the fracture (at 3 months, the distal locking screw had been removed for nail dynamization). Nail removal could be considered (e) (Fig. 18.33).

Note: 3.5 mm diameter was inappropriate: 4 mm nails should have been used.

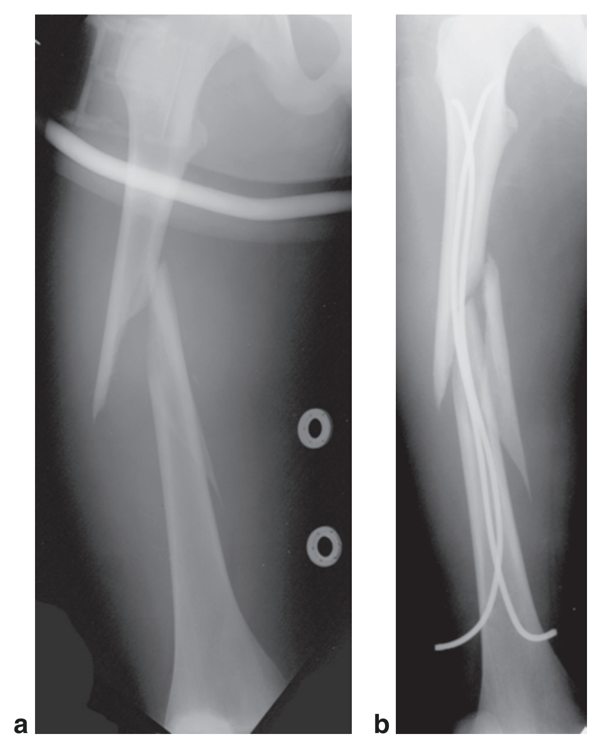


Fig. 18.33 Case 3

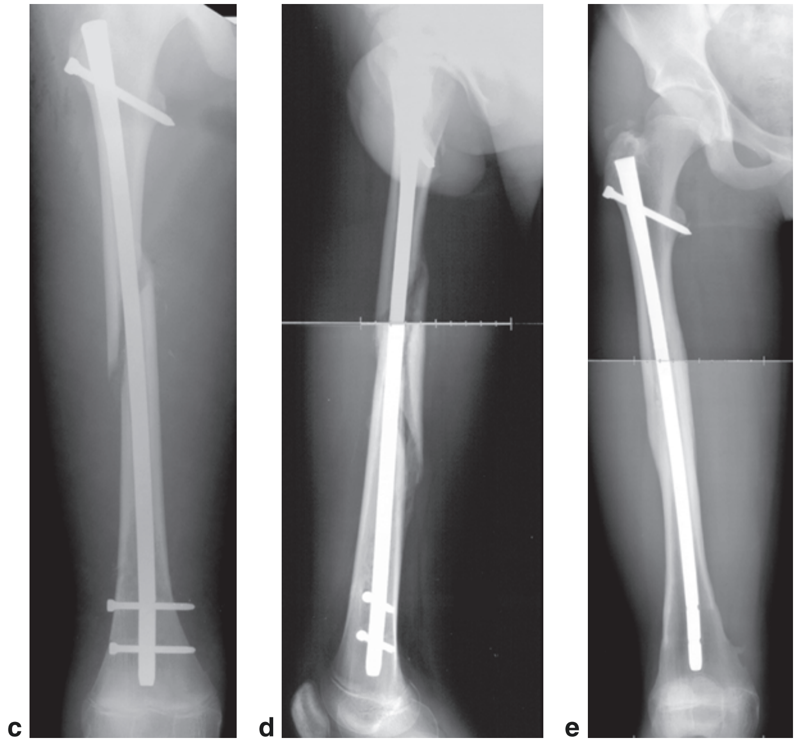


Fig. 18.33 (*cont.*) Case 3

18.7.4 Case 4

A 10-year-old boy with a proximal-third oblique fracture of the left femur (a) was treated with retrograde FIN using two 3 mm titanium nails (b, c). Two months later, he stumbled when getting out of a car and fractured again his femur: middle-distal third spiral fracture with the nails in situ. Callus formation was clearly visible proximally (d, e). The second fracture was managed under general anesthesia by external maneuvers. The nails were left in place. The thigh was immobilized in a splint for 2 weeks. Healing progressed uneventfully toward bone union, which took place in 4 months (f) (Fig. 18.34).

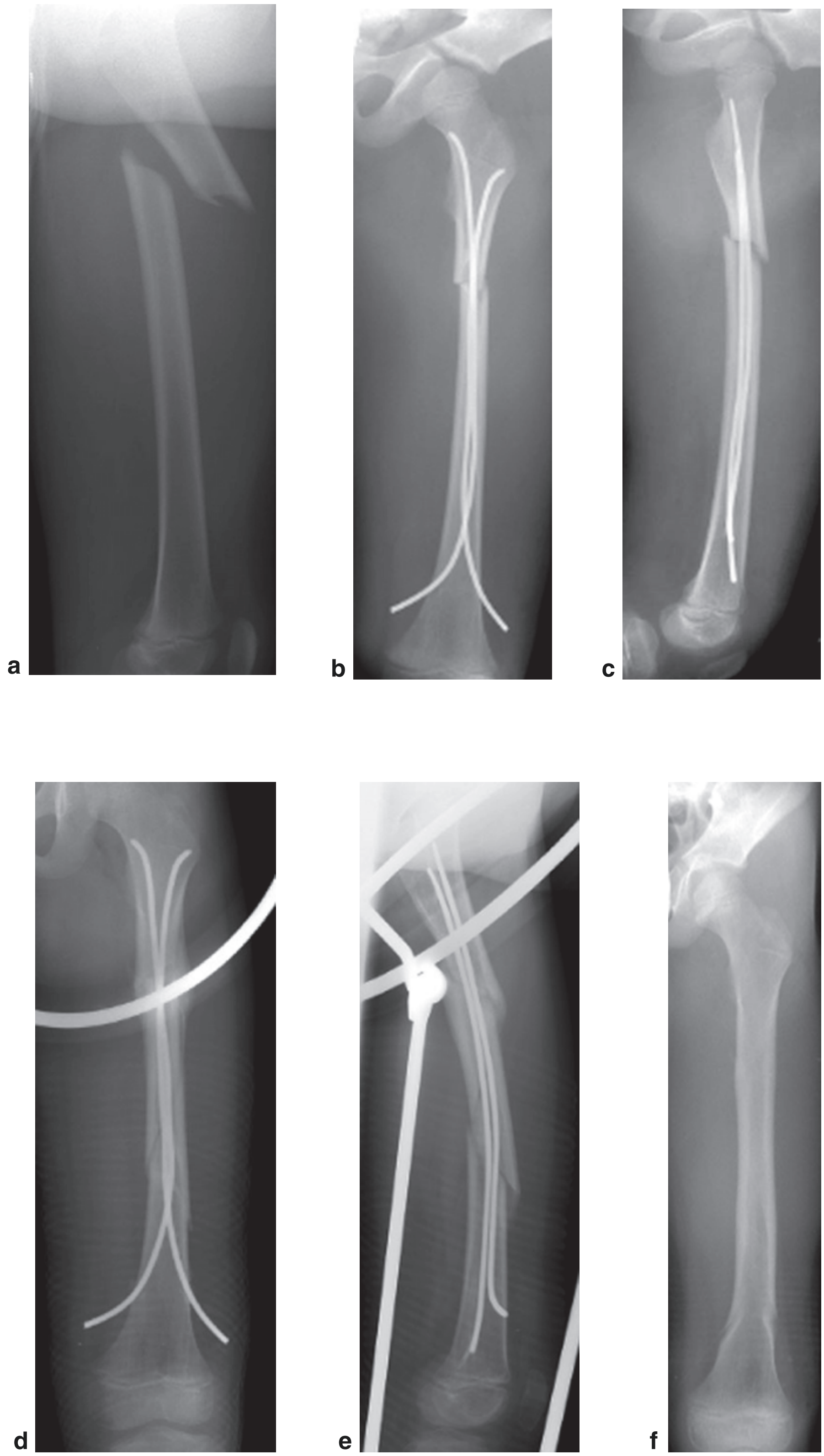


Fig. 18.34 Case 4

18.7.5 Case 5

A 7-year-old girl with a transverse fracture of the right femur due to direct impact (a metal rod hit her thigh) (a). Retrograde FIN was performed using two 3 mm titanium nails (b). One month later, she fell down and both nails got bent (c). Refracture was reduced under general anesthesia and the nails were straightened by hand. Stability was good (d). At 18 months, healing was complete, axial alignment was perfect, femur was 12 mm longer (e) (Fig. 18.35).

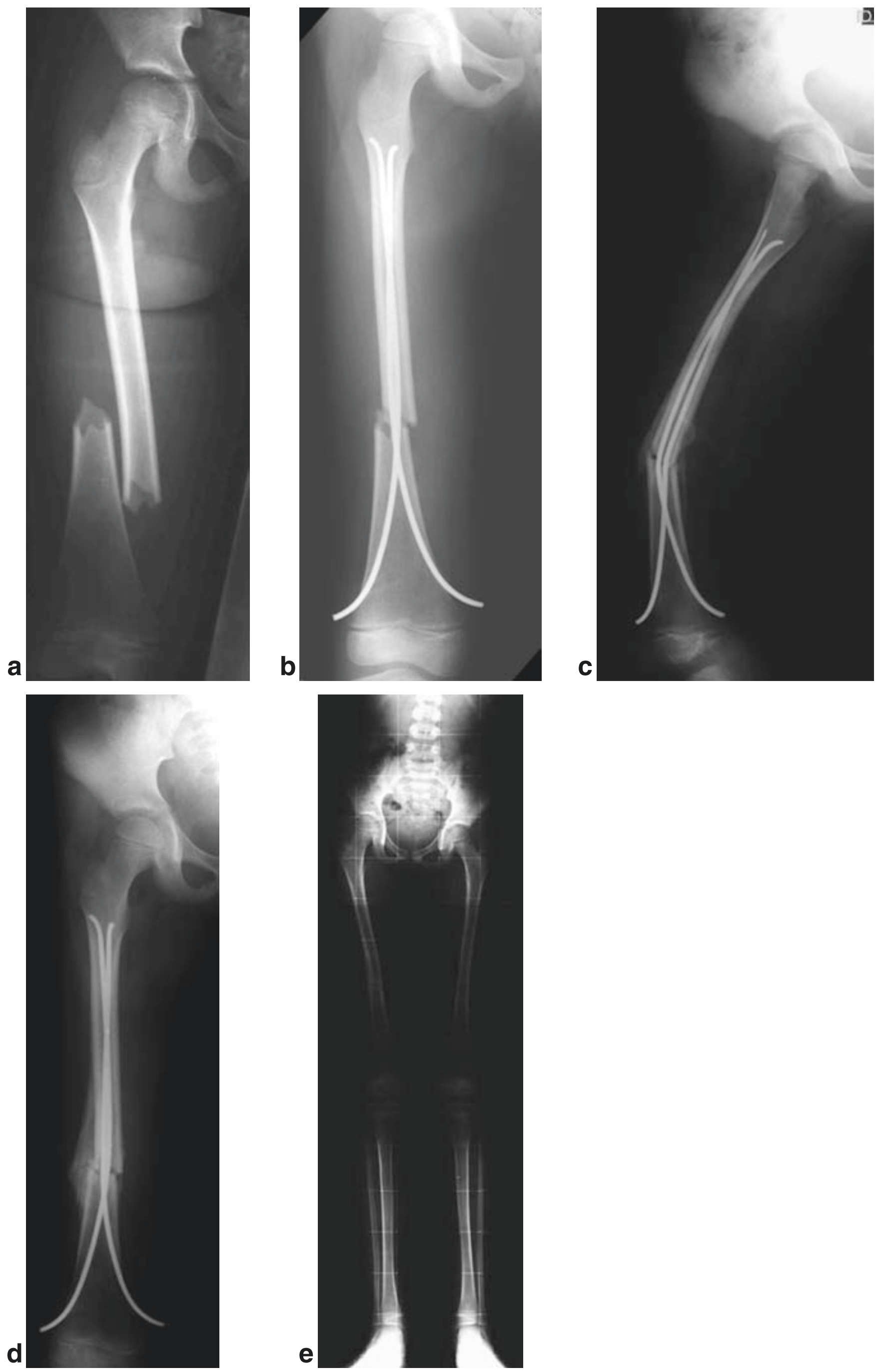


Fig. 18.35 Case 5

18.7.6 Case 6

An 11-year-old boy run over by a car presented with a Gustillo Type II open femoral fracture (with a large third fragment) (a). He was treated with bipolar retrograde FIN using two 3.5 mm titanium nails. The AP view showed that the nails crossed each other 3 times in the femur (b). The lateral view showed patent malrotation, which was not corrected (c). The fracture healed uneventfully (d) but there was clearly a rotational malunion with 40° retroversion of the right femoral neck, anteversion of the left femoral neck being 25° (e). Derotation osteotomy had to be performed secondarily (Fig. 18.36).

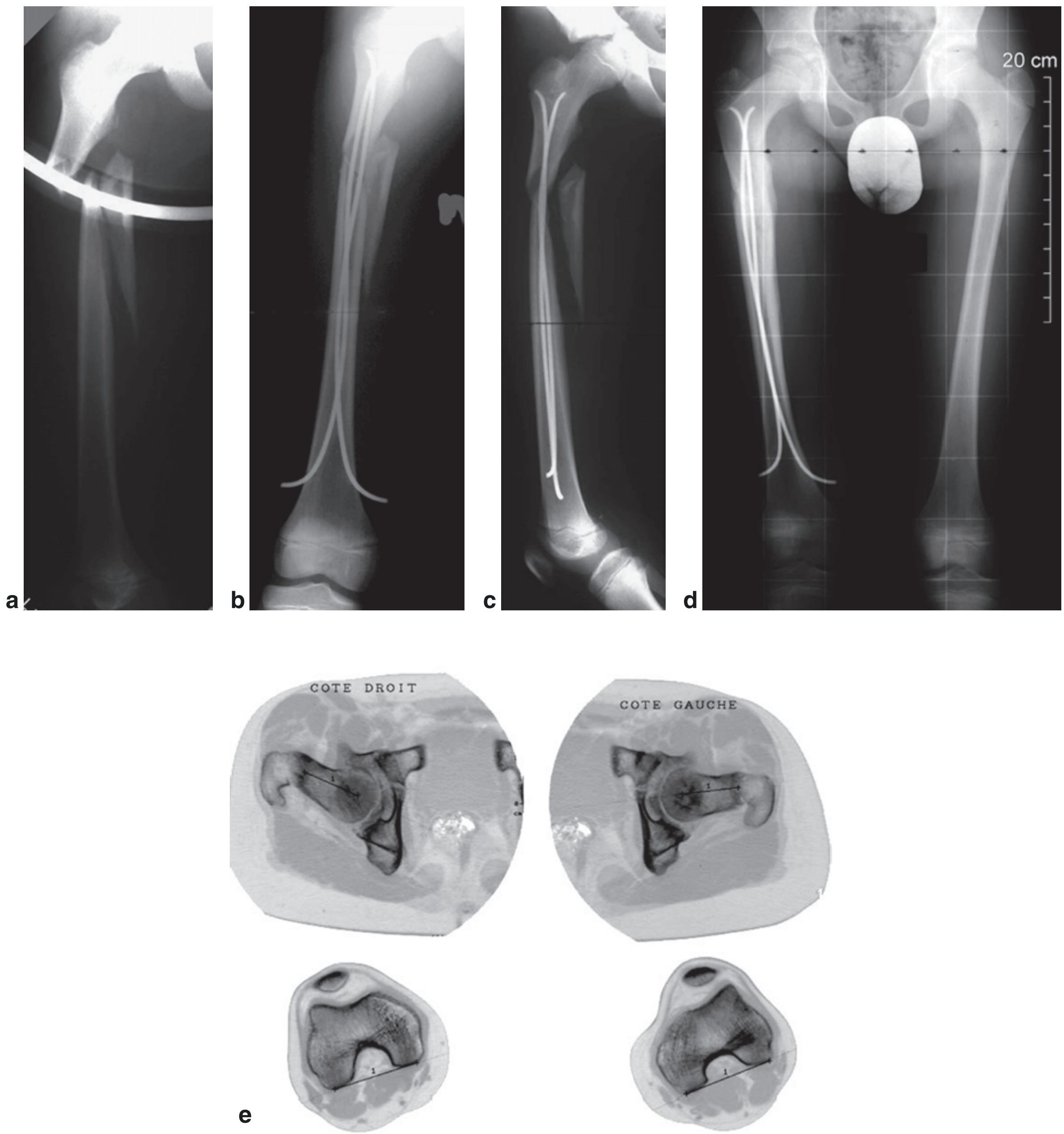


Fig. 18.36 Case 6

18.7.7 Case 7

A 12-year-old boy with a transverse fracture of the right femur sustained during a horse riding accident (a). Bipolar retrograde FIN was performed using two 3.5 mm stainless steel nails (b, c). Seven months later, he fell off a bicycle and sustained a distal-third fracture of the left femur (d). Again, bipolar retrograde FIN was performed using two 3.5 mm stainless steel nails. At 2 months, healing was going well. The child could return to his preinjury activities (e, f) (Fig. 18.37).

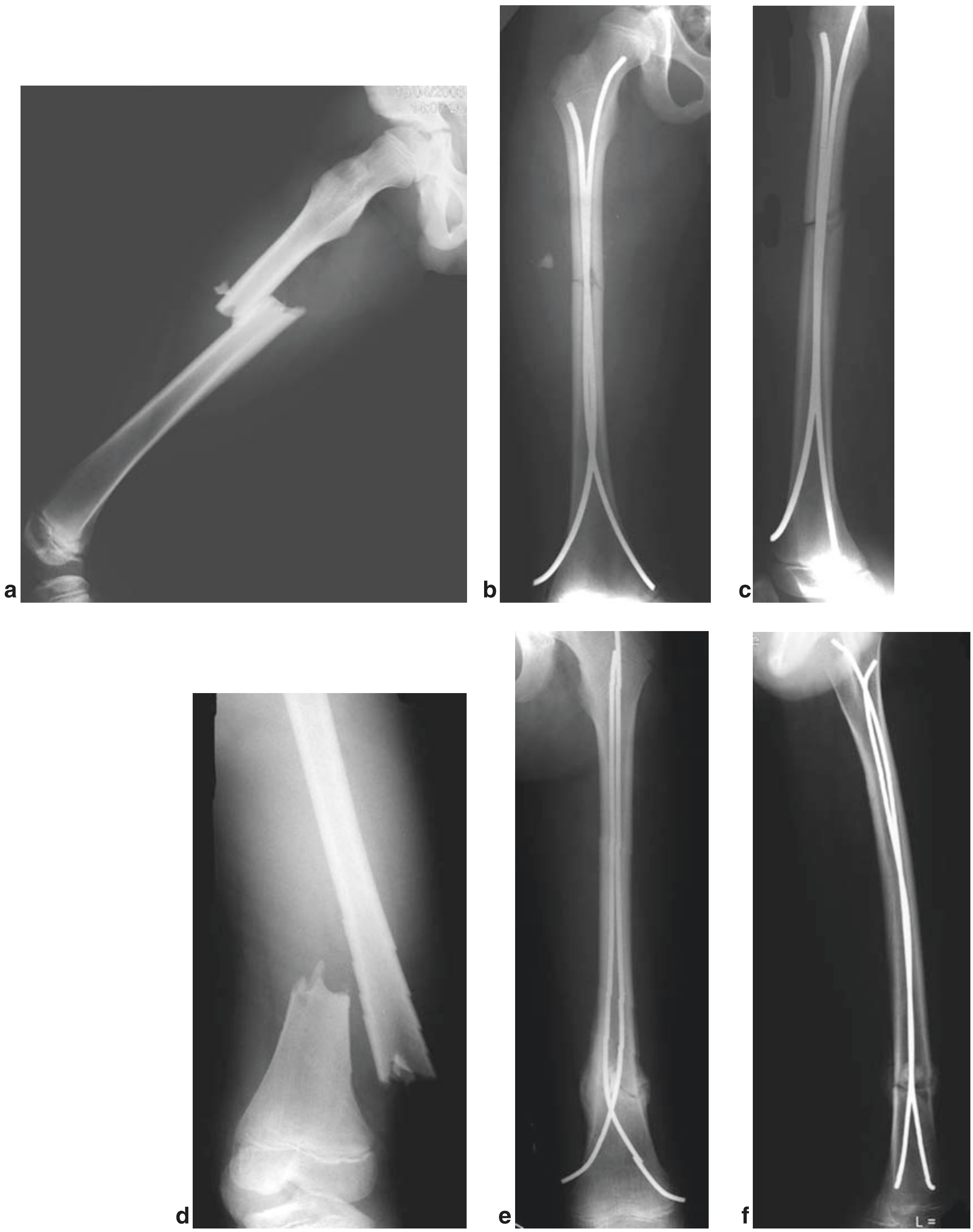


Fig. 18.37 Case 7

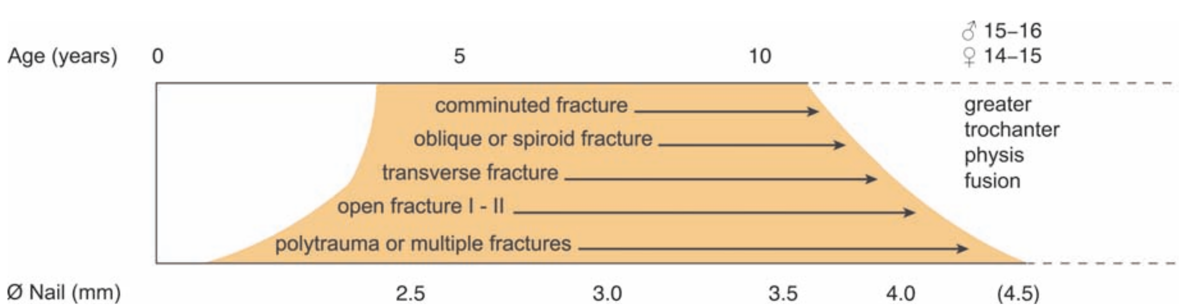
18.8 Six Key Points

- Reduction should be achieved in the frontal, sagittal, and horizontal planes.
- Avoid nail undersizing: most often, children more than 11–12 years old need 4 mm nails.
- Nail contouring is critically important to achieve adequate reduction: it means working in three dimensions.
- Nails should be pushed across the fracture site with the help of a slotted hammer.
- The finishing step requires great care: nail trimming, skin protection.
- Hardware should be removed before 6 months (unless otherwise required).

18.9 FIN and Femoral Fracture: Postoperative Management in the Absence of Complications

Day 0	• Postoperative AP and lateral radiographs • Entire lower limb is elevated • Foot may be stabilized by a sand bag • Pain killers ± antiinflammatories ± anticoagulant medication
Day 2	• First dressing • Rehabilitation: active contraction of the quadriceps, active mobilization of the foot
Days 2–8	• Patient is allowed up and encouraged to walk using two crutches (putting no weight on the injured leg) as early as possible • Discharge with instructions if healing progresses normally
Three to six weeks postop.	• Clinical and radiological (AP and lateral) follow-up • Partial weight bearing allowed at 3 weeks (transverse fractures) or 6 weeks (oblique and spiral fractures) • Anticoagulants are discontinued
Three to six months postop.	• Clinical and radiological (AP and lateral) follow-up • Nail removal is considered • Return to sports activities

18.10 FIN Indications: Femoral Fracture



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Tibial Fracture

19

Pierre Lascombes

19.1 General

19.1.1 Epidemiology

Tibia is the third most common location of diaphyseal fractures in children after forearm and femur, with a high prevalence (75%) in young boys around the age of 8. Their increasing incidence rate is attributable to road traffic accidents, and above all to injuries at sport (mountain bike, rollers, ski, snowboard, etc.) [2].

19.1.2 Mechanisms of Injury and Classifications

Isolated tibial fractures represent 70% of the cases. Isolated fibular shaft fractures will not be discussed in this chapter.

Oblique fractures (35%) and spiral fractures (15%) in the small child result from a twisting type motion. Complete fractures are much more frequent than greenstick fractures. In spiral fractures, it is not uncommon to have an isolated fracture of the tibial shaft with an intact fibula.

Transverse fractures (15%) rarely occur; they are due to a direct impact and may be associated with a third so-called "butterfly fragment."

Comminuted fractures (30%) are often severely displaced and associated with fracture of the fibula.

Tibial shaft fracture types typically seen in children include:

- Hairline fractures in infants, which are difficult to spot with X-rays.
- Plastic bowing fractures of the fibula, which may or maynot be associated with a tibial fracture.
- Stress fractures, which generally occur in the upper end of the tibia and in the mid-shaft of the fibula.
- Unicortical medial fractures of the proximal tibia, which are responsible for growth disturbance (i.e., progressive genu valgum).
- Diaphyseal fractures with extension into the proximal physis or, most often, into the distal physis.
- Open fractures, which are quite common considering the mechanisms of injury [5].

As far as stability is concerned, the following can be classified as stable:

- Isolated tibial fractures, particularly incomplete fractures. However, oblique tibial fractures with an intact fibula may shift into varus secondarily.
- Transverse fractures of the tibia and fibula.

Unstable fractures include: complete fractures of both bones of the leg, whether oblique, spiral or comminuted with a third fragment, which promote development of shortening or rotational malunion.

It is important to accurately evaluate the circumstances of the injury, as prognosis of tibial fractures is largely related to the amount of soft tissue bruising and the nonnegligible risk of compartment syndrome, and to bone devascularization, which may result in delayed union or even nonunion.

19.2 Antegrade FIN

19.2.1 Anesthesia

It is preferable to use general anesthesia as with nerve block a compartment syndrome might go undetected.

P. Lascombes, *Flexible Intramedullary Nailing in Children,*
DOI: 10.1007/978-3-642-03031-4_19, © Springer-Verlag Berlin Heidelberg 2010

19.2.2 Patient Positioning

The child is positioned supine on an operating table with a radiolucent foot section.

19.2.3 Image Intensifier

An image intensifier is placed at the foot of the table, which allows the surgeon and the assistant to stand on either side of the leg. The only disadvantage is that it may interfere with traction-reduction maneuvers. Alternatively, the image intensifier may be placed in front of the surgeon. Anterior–posterior views are easy to obtain; lateral views can be obtained either by externally rotating the lower leg en bloc, or with the C-arm in the horizontal plane (Fig. 19.1).

Fig. 19.1 *Right leg* has been sterile prepped. Image intensifier tibial crest and the head of the fibula is in front of the surgeon: the surgeon stands on the *right side*, the image intensifier is on the *left side*

19.2.4 Closed Reduction

Before prepping and draping, it is recommended to perform a manipulative reduction in order to memorize the maneuvers that will be repeated intraoperatively during nail insertion, and also to check for reducibility of the fracture. A proximal thigh tourniquet is placed if intraoperative difficulties are anticipated, but it is generally not inflated.

19.2.5 Operative Field

The entire lower limb is sterile prepped and a lower extremity surgical drape is placed.

19.2.6 Selection and Preparation of the Implants

Both stainless steel and titanium nails can be used:

- Nail diameter should meet the fundamental rule of flexible intramedullary nailing (FIN): nail diameter = 0.4 × diameter of the medullary canal. Therefore, the average diameter of the nail should be (depending on bone size):
  - 2.5 mm for a child aged between 6 and 8 years
  - 3 mm for a child aged between 8 and 10 years
  - 3.5 mm for a child older than 11
  - 4 mm for a skeletally immature adolescent
- Length of a fixed-length nail should be about 20 mm less than the distance from the proximal physis to the distal physis of the tibia.

The even-sized nails feature a tapered curved tip with an orthogonal projection length smaller than the diameter of the medullary canal. Both nails should be gently and identically contoured (about 40°) so that both concavities will face each other and both apexes will be located at the fracture site at the end of the procedure.

19.2.7 Surgical Approach

Two longitudinal incisions about 20 mm long are made in the medial and lateral aspects of the leg,

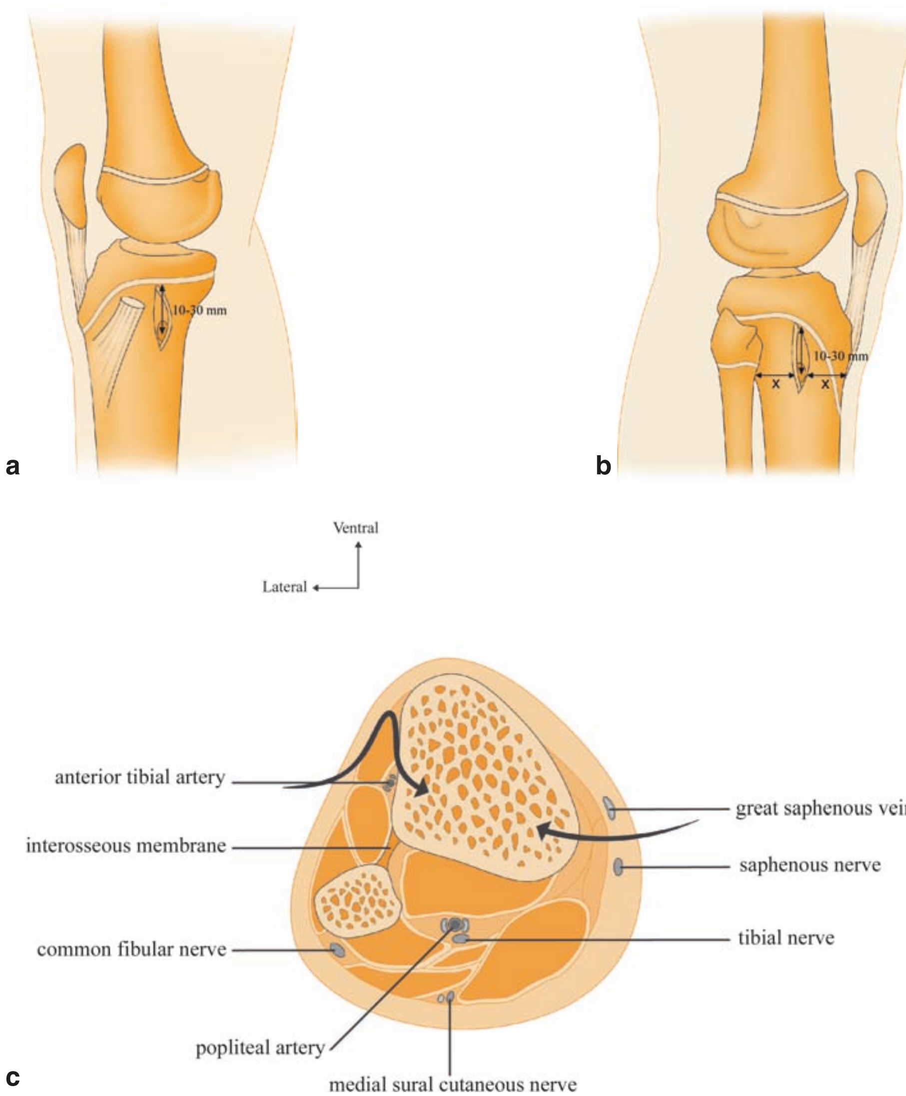


Fig. 19.2 (**a**) Medial approach to the proximal tibia: the entry hole is located in the midsection of the bone, between the insertion of the pes anserinus tendons and the medial collateral ligament, 10–30 mm distal to the proximal physis; (**b**) lateral approach to the proximal tibia: the entry hole is located in the midsection of the bone, anterior to the interosseous border of the tibia, 10–30 mm distal to the proximal physis; (**c**) transverse section through the proximal one-fourth of the leg showing medial and lateral approaches

approximately 10–30 mm distal to the proximal physis, which is easily palpable at the flare of the proximal tibia (Fig. 19.2). These incisions should not be placed too anteriorly to remain at some distance from the anterior tibial tubercle: a midline incision is made in the medial aspect of the tibia, and a lateral incision is made midway between the tibial crest and the head of the fibula.

19.2.7.1 Medial Nail

Medially, blunt scissors dissection is performed down to the cortical surface of the tibia, posterior to the midsection of the medial proximal metaphysis, close to the posteromedial border, 10–30 mm distal to the physis. The entry hole is made with an awl into the medial cortex of the proximal metaphysis, between the pes anserinus tendons and anterior to the tibial attachment of the medial collateral ligament. Then, the medial nail is attached to a T-handle (or inserter) and inserted through the entry hole: the curved tip is inserted perpendicular to the medial cortex; as soon as it makes contact with the far cortex, the inserter is rotated to direct the nail toward the medullary canal. The nail is advanced down to the fracture site using quick oscillary rotary motions (clockwise and counterclockwise) to prevent jamming in the cancellous bone trabeculae at the meta-diaphyseal junction.

19.2.7.2 Lateral Nail

Blunt scissors dissection is also used for the lateral approach. It is carried along the superficial fascia, which is retracted posteriorly together with the anterior compartment muscles. When the tips of the scissors reach the lateral cortex, they are held flush against the cortex and advanced posteriorly to the midsection of the bone. This point is located just anterior to the lateral border to which the interosseous membrane is attached. The entry hole is created with an awl, and the lateral nail is inserted and advanced using the same technique as previously.

19.2.8 Crossing the Fracture Site

Both nails are advanced down to the fracture site (Fig. 19.3), and fracture is reduced again using the same maneuvers. Adequate reduction is achieved when the tip of the lateral nail points laterally and the tip of the medial nail points medially. Then, each nail is carefully pushed across the fracture site using a mallet or a slotted hammer so as to avoid any motion at the fracture site or breakout of the cortex. In case of incomplete reduction, direction of one of the nails must be changed so that its tip points toward the opposite fragment. It may be directed medially or laterally, anteriorly or

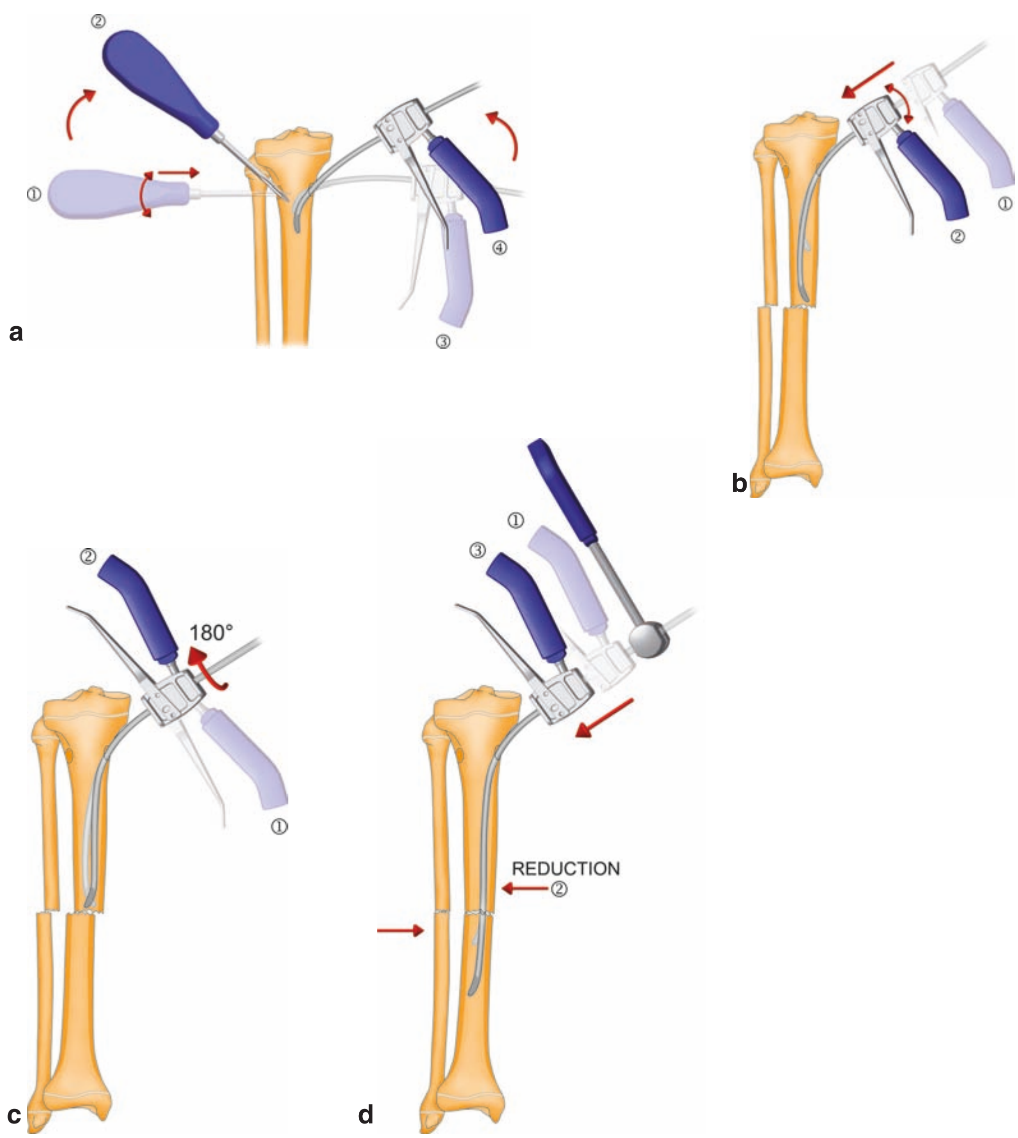


Fig. 19.3 Surgical technique: (**a**) the lateral hole is created with an awl and the medial nail is inserted through the medial entry hole; (**b**) the medial nail is advanced down to the fracture site; (**c**) the inserter is rotated 180° to direct the nail tip toward the opposite fragment; (**d**) the fracture is reduced and the medial nail is pushed across the fracture site using the slotted hammer

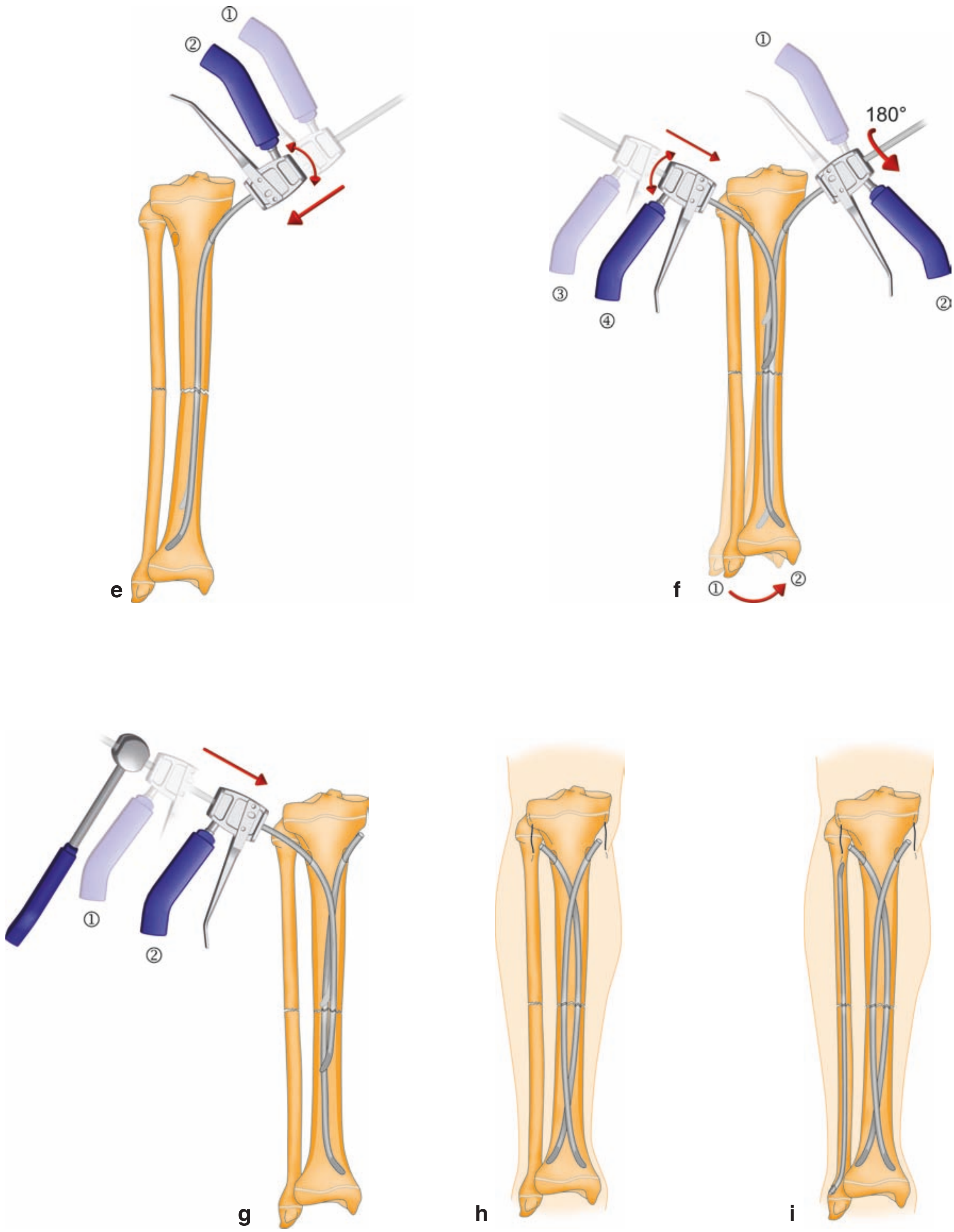


Fig. 19.3 (*cont.*) (**e**) Note the valgus angulation produced by the medial nail; (**f**) the medial nail is rotated 180° to correct angulation, and the lateral nail is brought to the fracture site; (**g**) the lateral nail is pushed across the fracture site; (**h**) final construct; (**i**) additional third fibular nail

posteriorly, or in combined directions as appropriate. Correct position of the nail tip is checked with image intensification in both the frontal and sagittal planes. Then, the nail is pushed using gentle hammer blows as previously described. Once it is inserted a few centimeters into the opposite fragment, bending and contouring initiate reduction of the fracture and facilitate passage of the second nail (properly oriented) through the fracture site.

19.2.9 Final Reduction

During the last step, orientation of the nails is fine-tuned so that the medial nail points medially and the lateral nail laterally. Final construct is technically perfect: two nails with opposing curves, the apexes of which are located at the fracture site.

Should mild displacement persist after both nails have entered the distal fragment, the surgeon can still use contouring to complete the reduction. A slight valgus angulation can be corrected by rotating the lateral nail 180° with its tip pointing medially (Fig. 19.4). A slight flexion angulation can be corrected by directing both nail tips anteriorly without changing their respective medial and lateral orientations: this is achieved by rotating the nails only 90°.

Conversely, a recurvatum angulation can be corrected by directing both nail tips posteriorly (Fig. 19.5). If anatomic reduction is achieved via nail orientation, the nail tips should be pushed into the metaphysis with the help of a slotted hammer. This allows to get a good purchase in the cancellous bone of the metaphysis and avoids destruction of bone trabeculae with rotary motions. Then comes final impaction of the fracture site.

19.2.10 Wound Closure

The proximal ends (trailing ends) of the nails are bent against the cortex and trimmed using a nail cutter that provides a smooth clean cut. The lateral nail end may be bent to about 60° to facilitate later removal. It is protectively padded by the overlying muscle mass, which eliminates the risk of postoperative skin lesions. Things are different with the medial nail, which lies right under the skin and must not be bent too sharply to reduce the potential for skin irritation. After trimming, a small subcutaneous pouch is created to allow the skin to smoothly glide over the nail and thus prevent adhesions. A cannulated impactor 7–12 mm long with a beveled tip has been designed for trimming to a precise length that is sufficient to facilitate later removal without causing skin irritation (Fig. 19.6).

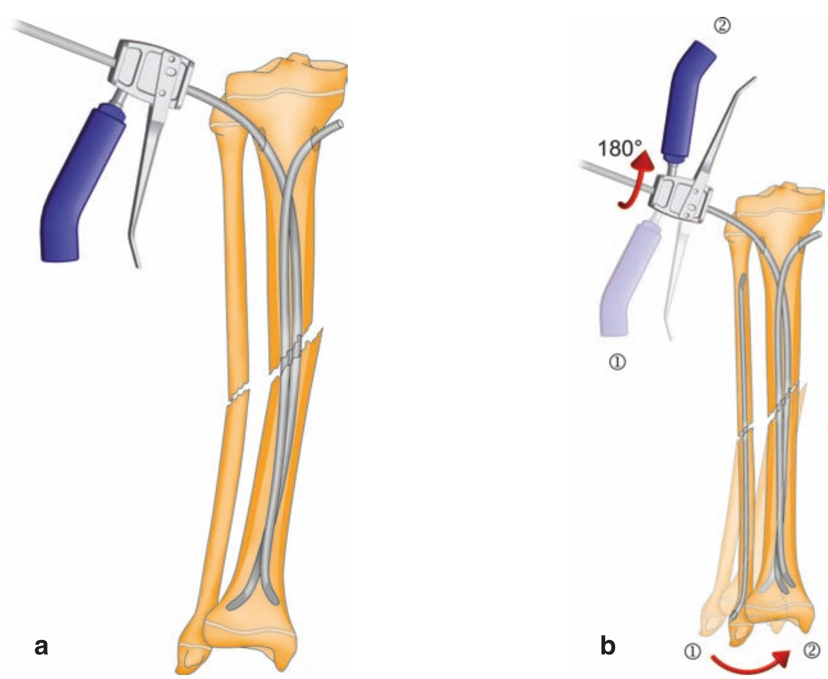


Fig. 19.4 Residual valgus angulation at the end of the procedure (**a**). Correction is achieved by rotating the lateral nail (**b**). Possibility to use a third retrograde nail in the fibula

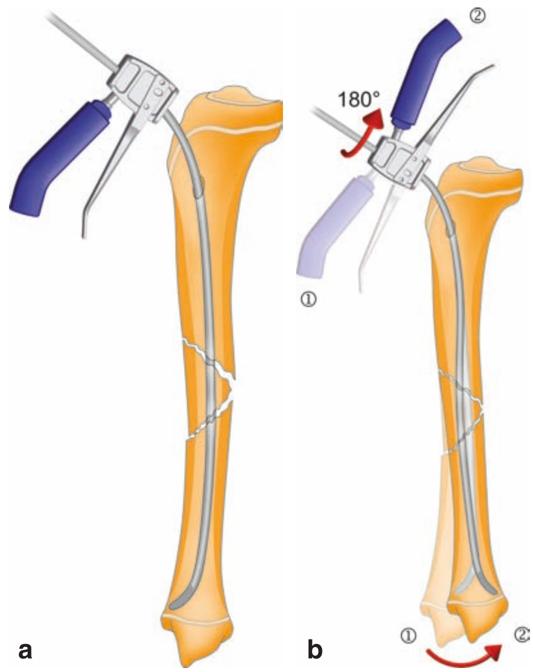


Fig. 19.5 Residual recurvatum angulation at the end of the procedure (**a**). One or both nails are rotated so that the tip(s) is/ are directed posteriorly (**b**)

The wound is copiously irrigated and closed in two layers.

Both knee and ankle joints are assessed in extension and flexion. Axial alignment is checked again in the frontal, sagittal and horizontal planes. A regular or compressive dressing is applied to the knee.

19.2.11 Types of Fractures

19.2.11.1 Fractures of the Distal Fourth of the Tibia

These fractures often have a transverse pattern resulting from a bending force to the tibia, or an oblique pattern. Many of them are classified as Type I or II open fractures (Fig. 19.7). The surgical technique is that of antegrade FIN as used for treatment of a diaphyseal fracture. However, contouring requires skillfulness even with prebent nails. The reason is the apexes of the curves must be eventually located at the fracture site, which is difficult to achieve because the nails tend to straighten within the medullary canal. Nevertheless, with final orientation of the nails and

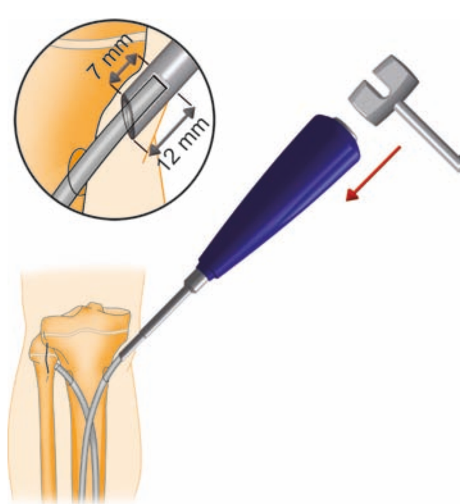


Fig. 19.6 Final impaction of the medial nail, trimming of the lateral nail, and closure of the wound

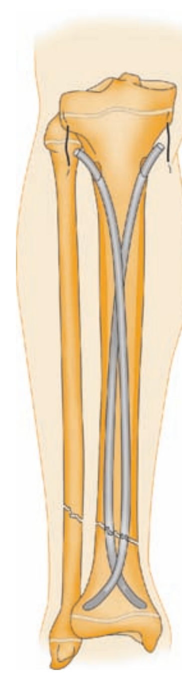


Fig. 19.7 Fracture of the distal fourth of the tibia: bipolar antegrade flexible intramedullary nailing (FIN). Note the distal location of both concavities

firm anchoring in the metaphysis, anatomic reduction can be obtained. Should this not be the case, the surgeon still has the option to apply a resin cast after a few days to correct alignment.

19.2.11.2 Fractures of the Proximal Fourth of the Tibia

Antegrade access to very proximal fractures of the tibia may be a real challenge. This is why retrograde FIN is the rule (Figs. 19.8 and 19.9). The technique itself is the same except that skin incisions are made in the distal tibia.

Lateral Nail

A 20 mm skin incision is made in the anterolateral aspect of the distal tibia, 40–50 mm proximal to the talocrural joint line. Tendons of the tibialis anterior and extensor hallucis muscles are retracted laterally to afford access to the bone and make the entry hole.

Medial Nail

In the supramalleolar region, the medial aspect of the tibia lies just under the skin. It is therefore advisable to move the skin incision to a more posterior position, that is, the posteromedial corner of the tibia where the entry hole is drilled with a 3 or 4 mm drill. This eliminates the risk of the awl slipping posteriorly.

The rest of the procedure is the same as for the lateral nail. Accuracy of final bending and trimming

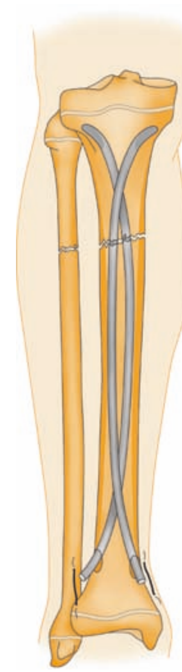


Fig. 19.8 Fracture of the proximal fourth of the tibia: retrograde FIN using two nails which intersect proximal to the fracture site

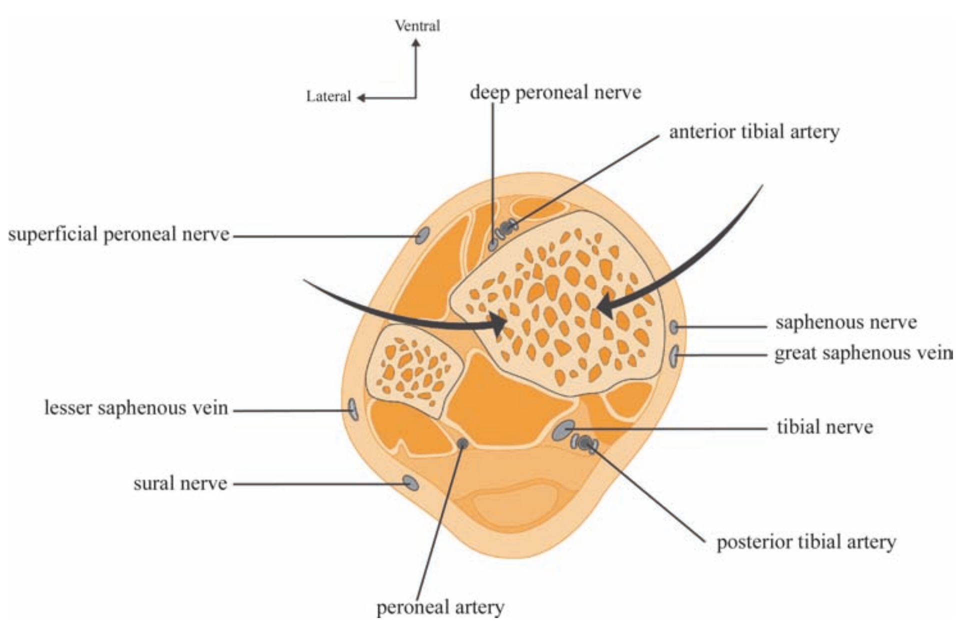


Fig. 19.9 Transverse section through the distal fourth of the leg showing medial and lateral approaches

above the ankle joint is essential to minimize the risk of postoperative skin lesions.

19.2.11.3 Nailing of the Fibula

In some circumstances, the surgeon may decide to nail the fibula, mainly to enhance the stability and the quality of tibial reduction. Usually, a supramalleolar retrograde technique is used and a single 1.5–2.0 mm diameter nail is inserted. The entry point is located 20 mm proximal to the distal growth plate of the fibula on the posterolateral aspect of the bone. This decreases the risk of skin lesion at the cut end of the nail as skin coverage on the anterior aspect of the fibula is too thin. The convavity of the nail must be oriented toward the tibia. The insertion technique is identical to that used in the forearm.

19.2.12 Postoperative Care

AP and lateral X-rays are taken. The lower leg is elevated for a few days and active range of motion is encouraged. Postoperative monitoring is focused on detection of compartment syndrome. Several times a day, the following are checked:

- Absence of pain.
- Normal flexion and extension of the toes, and normal dorsiflexion of the foot.
- Absence of sensory deficit in the foot, and particularly the first dorsal web space.

A simple dressing is applied and replaced on Day 2.

As soon as he/she can, the child is instructed and encouraged by the physical therapist to lift his/her leg off the bed, mobilize both the ankle and the foot, and work on knee locking in extension. Then, the child is allowed to get out of bed and ambulate with two crutches, being careful to put no weight on the injured leg. Discharge from hospital can be considered. Length of hospital stay does not exceed 3–5 days.

Both the child and the family are informed that subcutaneous prominence of the nails is absolutely normal and will disappear as soon as the nails are removed. Once the wound has healed, the child is requested to gently mobilize the skin area around the cut ends of the nails to prevent tissue adhesion.

19.2.13 Medical Treatment

Pain killers associated or not with antiinflammatories are prescribed until complete resolution of pain. DVT prophylaxis is routinely used in adolescents until full weight bearing is resumed.

19.2.14 Protection

Fractures that are anatomically reduced do not need postoperative immobilization. But, if residual angulation persists that cannot be possibly corrected through bone remodeling during the remaining growth period, immobilization in a cast or resin boot is necessary, plus gypsotomy in some cases. The boot is usually removed at 3 weeks.

19.2.15 Resumption of Activities

The child is able to return to school as soon as he/she is back home or after 1–2 weeks (at the most), as long as he/she is able to walk with two crutches.

Gradual weight bearing is begun after 2–4 weeks depending on the fracture type: it ranges from a couple of weeks for a transverse fracture to one full month for a long oblique or spiral fracture with one or several fragments.

At 2 months, the child should have a good ambulatory status and is able to evaluate his/her ability to resume gentle physical activities.

Clinical and radiological follow-ups are scheduled at 3 weeks, 6 weeks and 3 months postoperatively. Once union is complete, the nails can be removed.

19.2.16 Implant Removal

The nails can be removed under general anesthesia as soon as union is achieved, that is, from the third postoperative month. Titanium nails promote bone ongrowth so that removing the nails after a prolonged implantation period (i.e., 1 year) may be somewhat difficult. The dedicated instrument system includes strong locking forceps that can be used in combination with a slotted hammer. These instruments are most useful for extraction of 3.5 and 4 mm nails, which is sometimes difficult, particularly if the medial nail has been cut flush with the bone surface.

The removal procedure can be performed on a day patient basis using the previous scars. Immediate weight bearing is allowed but the child is requested to refrain from high-impact and collective sports for 2 months to reduce the risk of fracture at hole sites.

19.2.17 Postoperative Follow-Up

Depending on the age of the child and the presence or absence of residual angulation or other complications, static radiographs of the lower limbs are taken at 1 and 2 years to check for correct alignment and leg length equality. A child with an excellent outcome does not need further follow-up and is considered (legally) as permanently healed.

Any leg length discrepancy or malunion requires longer clinical and radiological follow-up (specific for pediatric patients).

19.3 Complications [4]

19.3.1 Difficult Reduction and Instability

Irreducibility of tibial fractures is so rare that we do not have one single open case to comment on.

On the other hand, incomplete reduction at end of the procedure is not uncommon and can be easily explained:

- In older children and young adolescents with an active proximal physis, which contraindicates the use of an intramedullary locked nail, perfect stabilization of highly unstable fractures (i.e., spiral fractures, long oblique fractures with a third fragment)

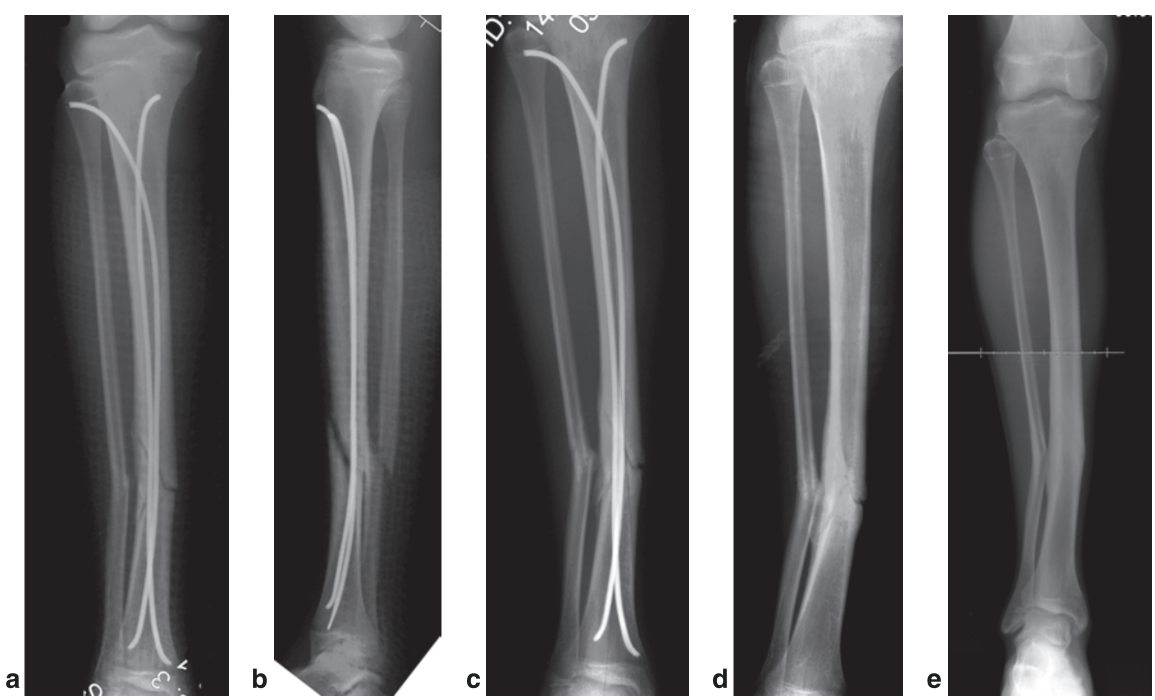


Fig. 19.10 A 14.5-year-old football player who sustained a mid-shaft tibial fracture with a third fragment. He was treated by FIN using 3.5 mm titanium nails. A residual 6° valgus angulation and mild recurvatum angulation failed to be corrected by a resin boot (**a**, **b**). At 3 months, valgus angulation was 9° (**c**). At 4 months, it was 15° and hardware had to be removed (**d**). One year later, the proximal physis had fused and valgus angulation was still 15°: corrective osteotomy was necessary (**e**). Note: the growth plate of the anterior tibial tubercle precluded insertion of an intramedullary locked nail. A FIN construct providing a varus counterforce plus a fibular nail would have prevented malunion

Fig. 19.11 A 13-year-old boy with fracture at the middle distal third junction. Addition of a retrograde fibular nail

cannot be reasonably expected (Fig. 19.10). As a matter of fact, due to the triangular geometry of the proximal tibia, it is difficult to respect the basic principle of the "two nails with opposing curves." In this situation, reorientation of the nails, use of a third tibial nail, or addition of a fibular nail may be a sound solution (Fig. 19.11).

- In cases where the fibula is intact, the potential risk of secondary varus shift can be avoided by positioning the two nails in a way that will produce a valgus counterforce: two lateral nails, or one medial nail and one lateral nail with their distal tips directed laterally (Fig. 19.12).

Should residual angulation persist, a cast or resin boot can be applied for 3–4 weeks. This conforming boot is usually effective in realigning the fracture (Fig. 19.13). If still insufficient, gypsotomy correction can be performed.

19.3.2 Implant-Related Problems

In fractures of the tibial shaft or distal fourth of the tibia, selection of the appropriate nail length is criticial to avoid cortical bone violation above the talocrural joint. Prominence of nail ends in the supramalleolar area where skin layer is thin may cause discomfort and pain.

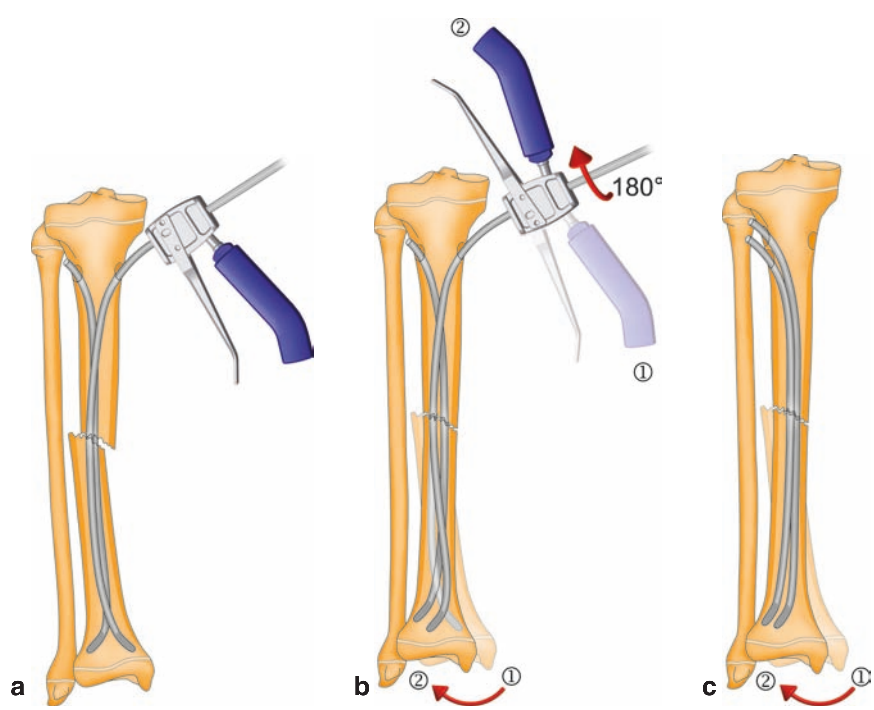


Fig. 19.12 Tibial shaft fracture with an intact fibula: (**a**) a theoretically "ideal construct" actually produced a varus angulation; (**b**) rotation of the medial nail with the nail tip directed laterally provided a valgus counterforce; (**c**) another option would have been to use two lateral nails that provide a valgus counterforce

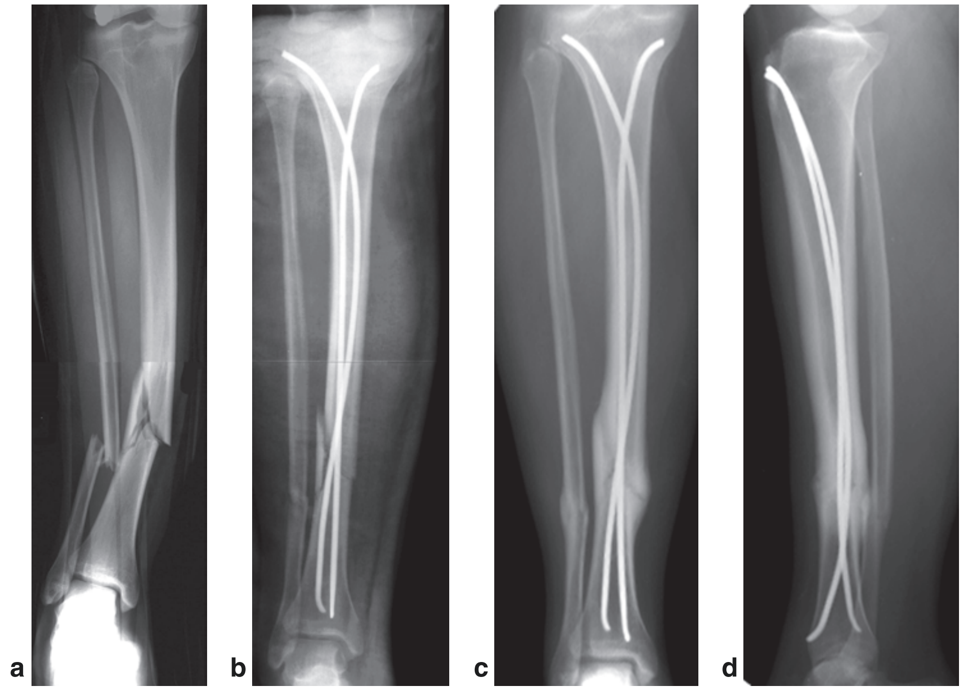


Fig. 19.13 A 15.5-year-old football player weighing 80 kg who sustained a fracture at the middle-distal third junction of the *right tibial shaft* with a third fragment, resulting from a direct impact (**a**). In spite of varus orientation of the 4 mm nails, both the presence of a third fragment and the intersection of the nails at the fracture site promoted valgus angulation of the fracture which was addressed by application of a cast boot for 1 month (**b**). Seven months later, normal function had been restored and the nails could be removed (**c, d**). Note: considering the child's age, an intramedullary locked nail could have been proposed

Fig. 19.14 Ulceration at the nail end: (**a**) prominent medial nail above the talocrural joint, anterior to the scar; (**b**) prominent medial nail at the proximal tibia with purulent ulceration

Proximally, cut ends do not generally pose problems on the lateral side where anterolateral compartment muscles provide efficient skin protection. But on the medial side where skin is in close contact with the bone, accurate trimming is critically important. As a matter of fact, if the nail is cut flush with the bone surface, it is very difficult to remove. On the other hand, if the nail end is too proud of the bone surface, once postoperative edema has resolved, it may protrude through the skin. If it occurs early, the surgeon may consider recutting the nail end or burying it in the bone. If it occurs 4–6 weeks postoperatively, it can be safely removed as the second nail remains in situ (Fig. 19.14).

19.3.3 Secondary Displacement

In theory, a proper FIN construct has inherent stability, which eliminates any risk of secondary displacement. However, a zero risk level is not attainable in severely comminuted fractures or if undersized nails have been used. In this case, loss of alignment is generally accompanied by impaction of bone fragments, which results in shortening of the bone, excessive prominence of the nail ends at entry holes, and angulation of the fracture site. Currently, the preferred method of treatment is the application of an external fixator for about 3–6 weeks to correct both the deformity and the shortening (Case 1).

a b

Fig. 19.15 A 14-year-old boy with a spiral fracture of the *right leg* sustained during a fall. Nonoperative treatment. After 24 h, a compartment syndrome was diagnosed requiring anterolateral and posterior fasciotomies, and FIN using 3.5 mm nails (**a, b**)

19.3.4 Vascular Complications

Vascular lesions are mostly seen in ipsilateral fractures of the lower limb, whether it be a “floating knee fracture” with a femoral and a tibial fracture, or a “floating ankle” injury.

19.3.5 Compartment Syndrome

A key advantage of FIN is that it facilitates close monitoring of the lower limb and detection of compartment syndrome at the early stage using conventional methods [7].

Whether it is revealed by typical clinical signs (i.e., pain, paresthesia, skin discoloration, muscle paralysis, and even disappearance of distal pulses) and/or by compartment pressure in excess of 30 mmHg, surgical fasciotomies should be performed using a standardized technique. FIN does not interfere at all with delayed wound closure (Fig. 19.15).

There is a specific form of compartment syndrome where only the extensor hallucis longus is involved. It manifests itself by loss of extension and sensory loss in the first web space that is indicative of a deep peroneal nerve lesion.

19.3.6 Infection

Osteomyelitis may develop, particularly in patients with open fractures. Most of the time, surgical treatment consists in: hardware removal, debridement, local drainage, external fixator if union is not yet achieved, and germ-specific antibiotics. Selection of the most appropriate treatment method should be based on: age of the child, severity of the sepsis, and experience of the surgical team (Case 1).

Fig. 19.16 A 14-year-old boy with a middle-third fracture of the *left lower leg* due to a direct impact, associated with a third "butterfly fragment" (**a**). FIN performed with undersized nails (3 mm) resulted in varus malunion (**b**). At 6 months, the fracture was not united. The case was revised with intramedullary locked nailing and osteotomy of the fibula (proximal growth plate had fused)

19.3.7 Joint Stiffness

When used in tibial fractures, FIN allows early mobilization of the knee joint and talocrural joint, thus minimizing the potential risk of joint stiffness.

19.3.8 Delayed Union and Nonunion

In young adolescents, transverse fractures or short oblique fractures with a third so-called "butterfly fragment" due to a direct impact are associated with a risk of delayed union and even nonunion. In our experience, we have had 2% nonunion (Fig. 19.16). This complication is partly due to the fact that fibular shaft fractures heal rapidly.

Around the third postoperative month, the fracture line is still visible and hypertrophic callus develops. Weight bearing is highly encouraged to promote healing; in some of our patients, union was achieved before the sixth postoperative month. In case of delayed union, mid-shaft osteotomy of the fibula is performed to remove about 10 mm of bone, which results in compression of the tibial fracture site and may promote union. Otherwise, nonunion must be treated. In a skeletally mature patient whose growth plate of the tibial tuberosity has disappeared, the FIN construct can be taken down and replaced by an intramedullary locked nail.

19.3.9 Difficult Implant Removal

Removal of the medial nail may pose a problem if the free nail end is too short to be grasped with the locking forceps. In this case, a small bone chisel may be used to chisel out the bone from around the nail end and facilitate removal. It should be kept in mind that a minimum 5 mm nail length must be left proud of the bone surface.

19.3.10 Malunion

Prevention of malunion relies essentially on the quality of the technique. Valgus/varus angulation can be addressed by directing the nail tips medially or laterally as appropriate to counter the angulation forces. The distal tip of the nail should be directed laterally to resist varus forces and medially to resist valgus forces.

Similarly, in the sagittal plane, the concave sides of the nails should face posteriorly to prevent recurvatum angulation (Fig. 19.6) and anteriorly to prevent flexion angulation of the fracture site. Combined deformities can also be addressed. For instance, a combined valgus-recurvatum angulation is addressed by directing the nails tips so that their convex sides face anterolaterally.

Once position and orientation of both nails are satisfactory, the nails are impacted into the cancellous bone of the metaphysis while maintaining reduction. Then, the proximal ends (trailing ends) of the nails are bent before trimming to secure the nails proximally.

Attention should be paid to the horizontal plane at all times during this reduction step to prevent rotational malunion (particularly, external rotation), which is very unlikely to remodel with growth. Again, if alignment of a lower leg fracture is not satisfactory after FIN, additional immobilization in a cast boot for 3–4 weeks plus gypsotomy (if necessary) must be proposed. In our experience, adjunctive immobilization was needed in almost two-thirds of our patients.

As the capacity for bone remodeling decreases with increasing age, it is generally held that varus and antecurvatum deformities cannot be corrected over the age of 12 years in girls and 13 years in boys, whereas a varus and/or recurvatum angulation that does not exceed 5° is acceptable [3].

19.3.11 Leg Length Discrepancy

No significant leg length discrepancy has been reported in isolated tibial fractures treated with FIN, firstly because overgrowth following fracture is greater in the femur than in the tibia and secondly because children treated with FIN are generally more than 10 years old (Case 2).

19.4 Indications [6, 9–12]

19.4.1 Multiply Injured Patients

In patients where vital signs have been stabilized, tibial fractures in multiply injured patients are excellent indications for FIN.

As a matter of fact, FIN facilitates postoperative care, muscle compartment monitoring and skin condition monitoring. Furthermore, it eliminates the risk of castrelated problems. In coma patients, passive rangeofmotion exercises, splinting and application of other devices to prevent stiffness and contractures (particularly, in knee and foot) can be initiated early.

19.4.2 Open Fractures

While Type III open fractures are generally treated with external fixation [1, 8], Type I and II open fractures are good indications for FIN, which is performed after careful debridement of the fracture and prophylactic antibiotics. Wound monitoring is easy and it eliminates the risk of secondary displacement with windowed plaster support.

Fractures with no skin wound but severe bruising are also good indications for FIN as it facilitates assessment of local condition and early detection of skin necrosis. It also facilitates additional procedures such as flap coverage.

19.4.3 Instability

FIN is used in immediately unstable fractures, which are not amenable to nonoperative treatment, and secondary displacements with plaster support that failed to be corrected even through gypsotomy. Patients requiring surgical revision 1 week after adequate nonoperative treatment was performed can be benefited by FIN (Case 3).

19.4.4 Age of Patient

Age of patient is not a major consideration for FIN in tibial fractures, but it is often correlated with multiple injuries, instability and associated skin lesions.

19.5 Contraindications and Limitations

Type III open fractures are best treated with an external fixator.

In adolescents, fusion of the proximal physis defines the upper age limit for FIN. These patients are preferably treated with intramedullary locked nailing, which eliminates the need for additional cast immobilization and reduces the potential for malunion and delayed union.

19.6 Case Reports

19.6.1 Case 1

A 15-year-old boy with a comminuted fracture of the right tibial shaft and compartment syndrome sustained during a motorcycle accident (a, b). Fracture was associated with ipsilateral avulsion of the posterior cruciate ligament and overstretching of the anterior cruciate ligament. Growth plate of the tibial tuberosity was still active. The patient was treated by tibial FIN using two 3.5 mm titanium nails and fasciotomies. During the third week, a secondary displacement occurred with severe recurvatum angulation (c, d), which required application of an external fixator for 6 weeks (e, f). Union was achieved at 6 months and the nails were removed (g, h). Ten months later, osteitis occurred at the fracture site with fistula formation and subcutaneous abscess. *Staphylococcus meti-S was identified (MRI) as the source of infection* [L. Mainard] (i) [axial T1-weighted gadolinium-enhanced fat-saturated MR image], (j) [sagittal T1-weighted gadolinium-enhanced fat-saturated MR image], (k) [Ectricks MRI technique]. Patient was cured after surgical debridement and antibiotics for 3 months (l, m) (Fig. 19.17).

Note: nail diameter was very small; 4 mm nails would have been preferable.

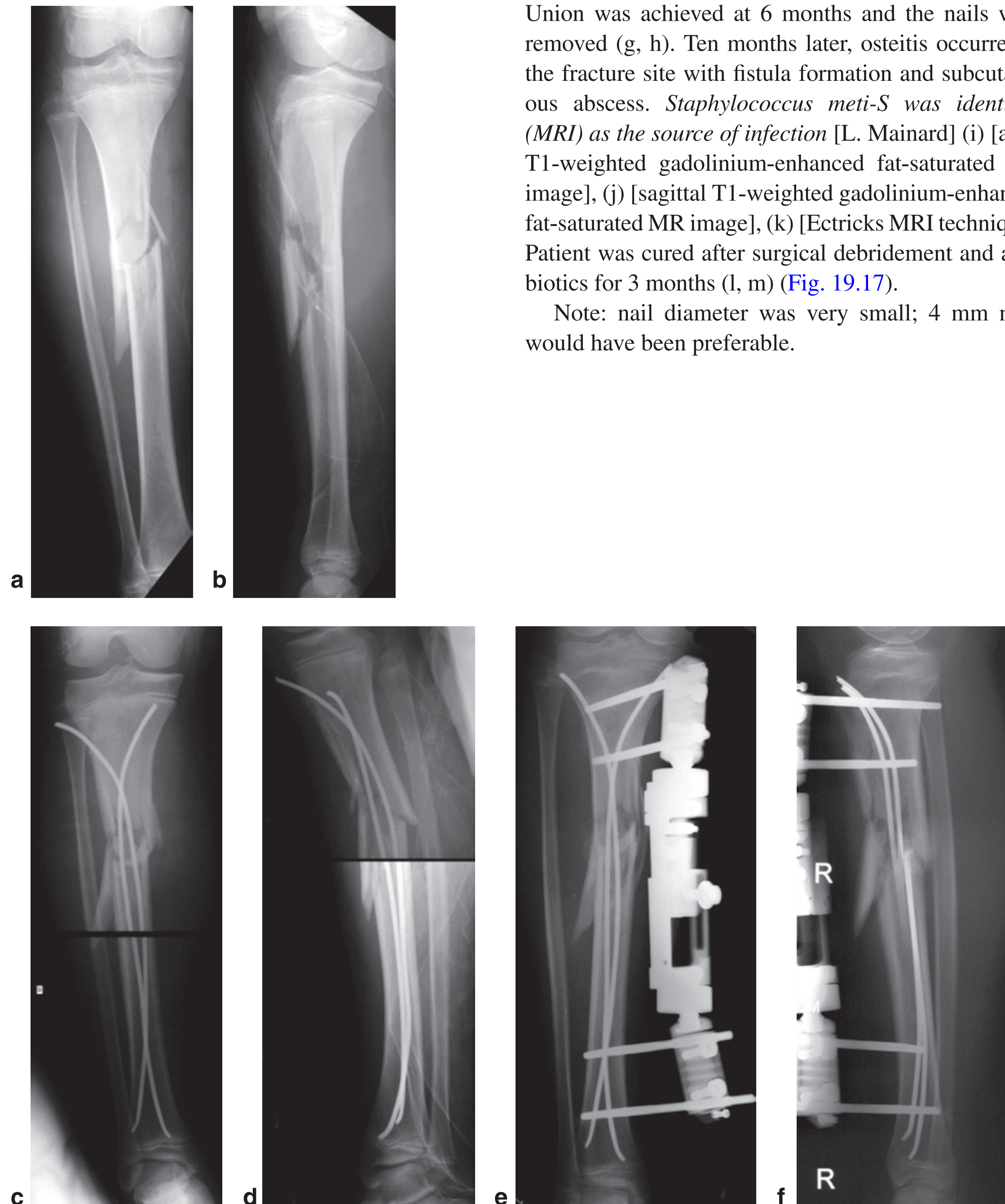


Fig. 19.17 Case 1

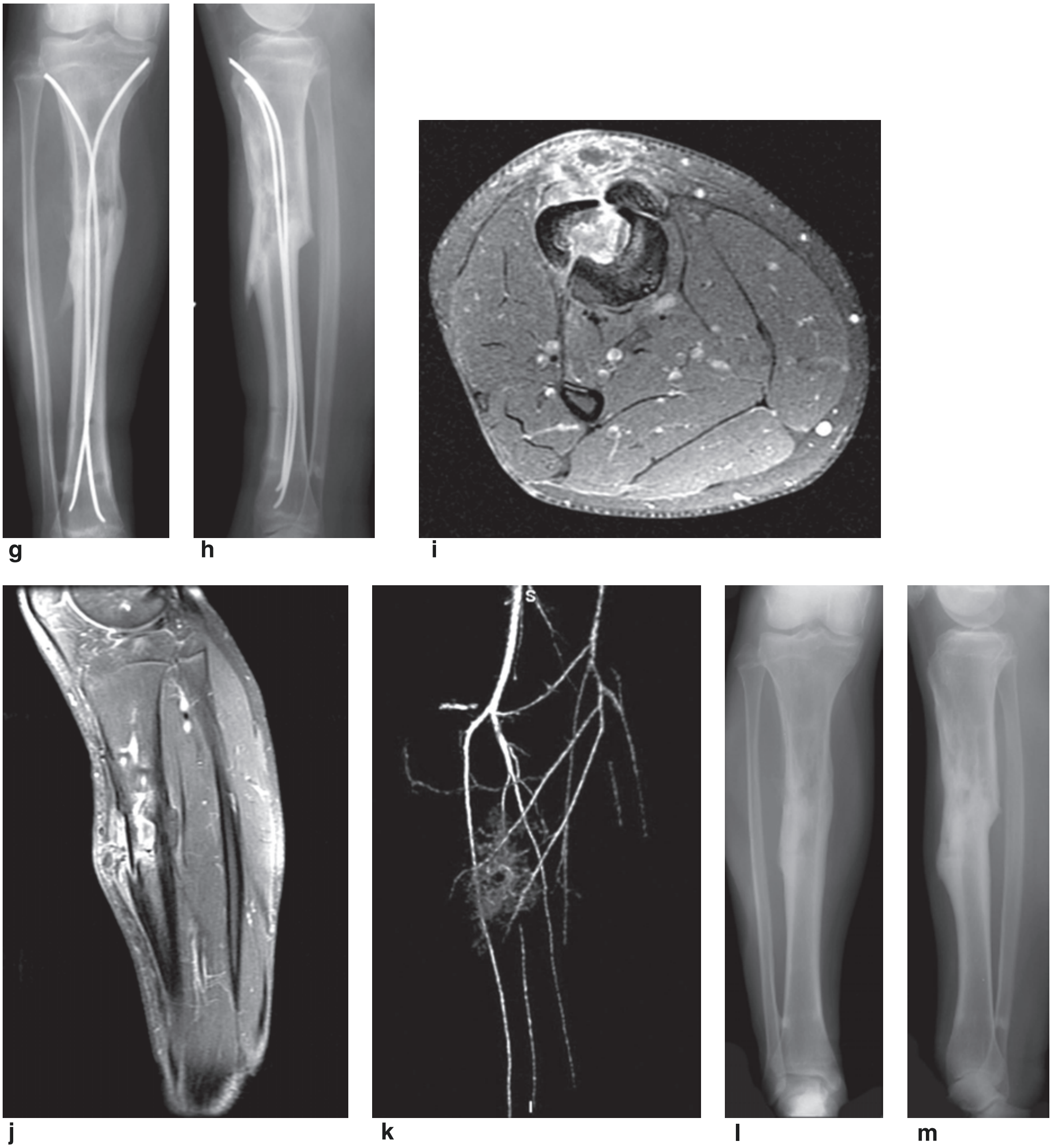


Fig. 19.17 (*cont.*) Case 1

19.6.2 Case 2

A 6.5-year-old boy run over by a car sustained head injury, uncomplicated pubic symphysis separation, and Type II open fracture of the right lower leg (a). Emergency surgical debridement and FIN (2.5 mm nails) were performed (b, c) in association with subcutaneous posterior and anterolateral fasciotomies due to high compartment pressure (>40 mmHg). After 6 weeks, healing was progressing towards union (d, e). One year later, the nails were removed. At 2 years, function was normal and axial alignment was perfect. However, the right tibia was 16 mm longer than the left one. Postoperative overgrowth phenomenon was evidenced by the asymmetric pattern of Harris lines.

Note: significant overgrowth may occur (Fig. 19.18).

Fig. 19.18 Case 2

19.6.3 Case 3

A 14.5-year-old boy sustained a tibial fracture while skiing and was treated nonoperatively. X-rays taken 10 days postoperatively showed a recurvatum angulation that had occurred secondarily (a, b). He was treated by FIN using 4 mm nails (c, d). Three months later, union was achieved (e, f) and nails could be removed (Fig. 19.19).

Note: entry holes were in a low position.

Fig. 19.19 Case 3

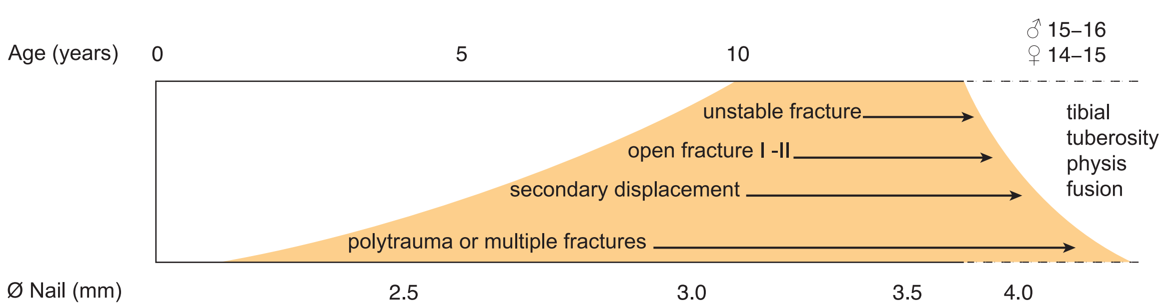
19.7 Six Key Points

- Reduction should be achieved in the frontal, sagittal, and horizontal planes (malrotation).
- Nails should be pushed across the fracture site with the help of a slotted hammer.
- Nails must be oriented according to the axial deformity; fibula can be nailed, if necessary.
- Quality of trimming and length of free ends are critically important.
- Close monitoring for detection of compartment syndrome.
- In case of residual axial malalignment, a cast boot may be applied for 3 weeks.

19.8 FIN and Tibial Fracture: Postoperative Management in the Absence of Complications

Day 0	• Postoperative AP and lateral radiographs • Close monitoring for detection of compartment syndrome • Lower leg is elevated • Pain killers ± antiinflammatories ± anticoagulant medication
Day 2	• First dressing • Rehabilitation: active mobilization of lower limb, knee, foot
Days 2–6	• Patient is allowed up and encouraged to walk using two crutches (putting no weight on the injured leg) as early as possible • Return to school as soon as possible
Three to six weeks postop.	• Clinical and radiological (AP and lateral) follow-up • Partial weight bearing progressing to full weight bearing (before the sixth week) • Anticoagulants are discontinued
Three to six months postop.	• Clinical and radiological (AP and lateral) follow-up • Nail removal is considered after 3–4 months • Return to sports activities
Eighteen to twenty-four months postop.	• Clinical and radiological follow-up: standing X-rays of the lower limbs

19.9 FIN Indications: Tibia



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20 Ipsilateral Long Bone Fractures and Polytrauma

Pierre Lascombes

20.1 Ipsilateral Long Bone Fractures

Ipsilateral long bone fractures account for less than 5% of injuries of childhood, and require appropriate surgical strategies: which ones should be treated by internal fixation? What is the fixation sequence? Are there specific complications [1–3]?

20.1.1 Floating Joint Injury

Diaphyseal and/or metaphyseal fractures, which occur on both sides of a joint result from very high-energy trauma. The severe displacement of bone fragments, which typically occurs in these injuries, is potentially responsible for vascular lesions. A "floating knee" injury is often associated with ischemia of the lower leg and foot due to a lesion of the popliteal artery, either at the tibial fracture site if located in the proximal metaphysis, or beneath the fibrous arch of the soleus muscle [4, 5].

Vascular injuries are also encountered in "floating ankle" injuries – ipsilateral tibial shaft and foot (talus) fractures – (Fig. 20.1), or "floating elbow" injuries – ipsilateral fractures of both bones of the forearm and distal shaft of the humerus. In the latter case, the vascular injury sits either at the fracture site in the lower end of the humerus, or beneath the superficialis arch.

As regards management of distal ischemia, we have personally been led to use a standardized protocol customized to our health care center. Ideally, high-quality angiography should be performed upon admission to the emergency department, but in practice, we are faced with situations where the patient (often multiply injured) is transferred from a distant emergency center. Therefore, we routinely proceed as follows: resuscitation, assessment of injuries, immediate treatment. Fractures are reduced and stabilized either by internal fixation (flexible intramedullary nailing FIN), or by external fixation in open fractures. The next steps are contingent on the vascular status of the patient:

- If peripheral pulses reappear postoperatively, close monitoring is imperative for early detection of compartment syndrome, as it is in direct relationship with the duration of ischemia. Complete fasciotomy of all compartments is often mandatory. When in doubt, better to propose it.
- If peripheral pulses do not reappear and no Doppler signal of arterial flow can be obtained, and yet, a capillary pulse is detected with normal skin color at extremities, ischemia can be temporarily ruled out. Angiography or other vascular exploration using vascular imaging is performed within the following days to delineate the exact nature of the lesion and allow the surgeon to decide whether arterial repair should be considered.
- If ischemia persists, emergency surgery is proposed: vascular exploration by dynamic imaging techniques is time-consuming, and any time wasted may be detrimental to the patient. The artery is approached at the fracture site which is likely responsible for the vascular insult, or at the fibrous arch. Entrapment of the artery within the fracture site is easy to manage, whereas repair of traumatic intimal dissection or even arterial rupture involves resection of the injured area, including a few millimeters of intact area on both sides and interposition of autologous vein graft. At the end of the procedure, compartment fasciotomies are routinely performed to protect as much as possible against potential sequelae of neural ischemia.

P. Lascombes, *Flexible Intramedullary Nailing in Children,*
DOI: 10.1007/978-3-642-03031-4_20,

Fig. 20.1 A 4.5-year-old boy who was a passenger in a car crash. Both front-seat passengers died. The young child sustained head trauma, closed fracture of the distal fourth of the tibia (**a**), and fracture of the right talus (**b**). Surgical exploration of this "floating ankle" injury revealed disruption of the anterior tibial artery at the tibia and disruption of the dorsalis pedis artery at the talus. All anterior compartment muscles were ruptured. Muscle repair, vascular bypass and extensive fasciotomies were performed. The tibial fracture was treated by antegrade flexible intramedullary nailing (FIN) using two 1.5 mm stainless steel nails and fracture of talus with K-wires (**c**, **d**). Skin necrosis developed and required transfer of a latissimus dorsi free flap. Later on, osteonecrosis of the talus occurred and ossification developed, resulting in restriction of dorsiflexion of the foot. The tibial fracture healed uneventfully (**e**, **f**). Note: ipsilateral joint injuries are always associated with extensive soft tissue damage

20.1.2 Ipsilateral Fractures of the Femur and Tibia

Whatever the age of the child, as long as physes are still open, femoral fractures should be preferably treated by FIN. In adolescents with fused growth plates, intramedullary locked nailing is recommended. In open fractures, surgical debridement should be performed prior to external fixation. In the tibia, the surgical strategy depends on the anatomic location of the fracture: [6]

- Diaphyseal fracture: a 10-year-old child who has a fracture with little or no displacement and no vascular disorders can be treated nonoperatively by a long-leg cast. In this case, FIN of the femur is done first. Then, a long-leg cast is applied, though knowing the difficulty to detect a compartment syndrome with plaster support. In children aged more than 10 years or for treatment of a closed tibial fracture that is assumed to be unstable, FIN of the tibia is performed first, with the patient placed on a standard operating table (Fig. 20.2). If it is an open fracture, surgical debridement is followed by application of an external fixator. Then, the patient is positioned on a fracture table for FIN of the femur. Experience shows that it is preferable to do the femur after the tibia (whether it is managed with FIN or external fixation) (Fig. 20.3). In order to avoid traction on the tibia that is already fixed, it is recommended to insert a temporary tibial pin at some distance from the tibial tuberosity.
- Proximal metaphyseal fracture or epiphyseal separation at the proximal tibia: retrograde FIN may be

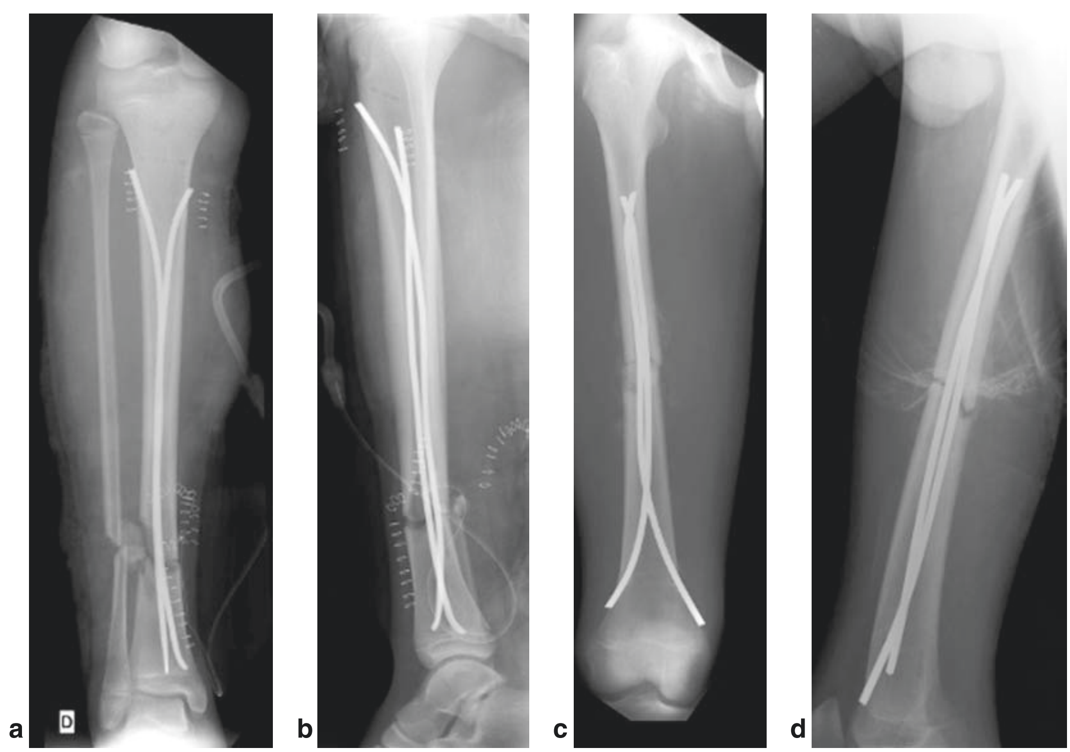

Fig. 20.2 A 14-year-old boy who was a passenger in a car crash. He suffered multiple injuries: facial wounds, dislocation of the *left hip joint*, fracture of the *left talocrural joint*, plus in the *right lower limb*: open femoral fracture and open fractures of both tibia and fibula. The patient was operated on in emergency: reduction of the dislocation, fixation of the *left talocrural joint* fracture, surgical debridement of fractures of the tibia and fibula followed by antegrade FIN using two 4 mm titanium nails. Both nails were directed medially to prevent valgus angulation. There was a residual flexion angulation of 5° (**a**, **b**). Lower limb fasciotomy was necessary; after placement of a tibial traction pin, the patient was positioned on a fracture table to perform surgical debridement and FIN of the right femur using two 4.5 mm stainless steel nails (**c**, **d**). Note: flexion angulation could have been avoided had the anterolateral tibial nail been directed anteriorly

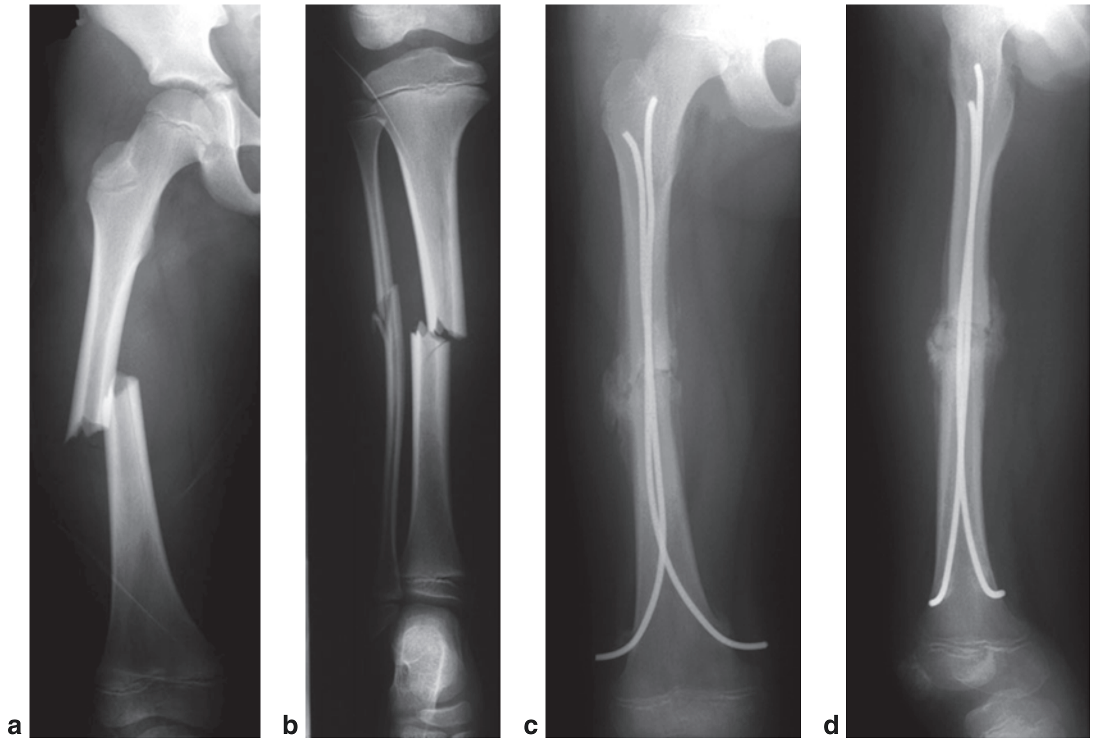

Fig. 20.3 A 11-year-old biker was run over by a car. The young boy suffered multiple injuries: head trauma, cervical sprain, abdominal contusion with effusion, ipsilateral fractures of the *right femur* and tibia (**a**, **b**). The child was treated in emergency. The procedure was performed on a fracture table: both fractures were fixed with FIN; femur was treated first by retrograde FIN using two 3 mm titanium nails. At 6 weeks, healing was progressing uneventfully (**c**, **d**)

proposed, though technically demanding and requiring a certain amount of experience; internal fixation is contraindicated due to the potential risk of physeal injury. For this reason, Monolateral External Fixator is most often the treatment of choice. Furthermore, being positioned anteriorly, it does not impede access to the vascular structures lying on the posteromedial aspect of the knee. Then, FIN of the femur is performed on a fracture table. However, in order to shorten the operation time and reduce potentially deleterious traction maneuvers, FIN of the femur may be performed on the same operating table, even if it means using an open approach to reduce the fracture and push the nails across the fracture site under visual control.

As regards specific complications, one must not forget that long-bone overgrowth that occurs in children aged less than 10 years is a cumulative phenomenon: about 10 mm in femur plus 5 mm in tibia [7–9].

20.1.3 Ipsilateral Fractures of the Humerus and Forearm

Humeral fractures (i.e., fractures of the upper end of the humerus, humeral shaft fractures, supracondylar fractures of the humerus) associated with forearm fractures can be successfully treated by multiple nails. In practice, it is easier to begin with the humeral fracture and then treat the forearm fracture. In order to avoid inopportune traction maneuvers, one or two forearm fractures may be treated using an open approach, which will facilitate FIN (Fig. 20.4).

20.2 Polytrauma

Our experience shows that almost one in two femoral fractures is associated with another injury such as head trauma, thoracoabdominal contusion, pelvic trauma,

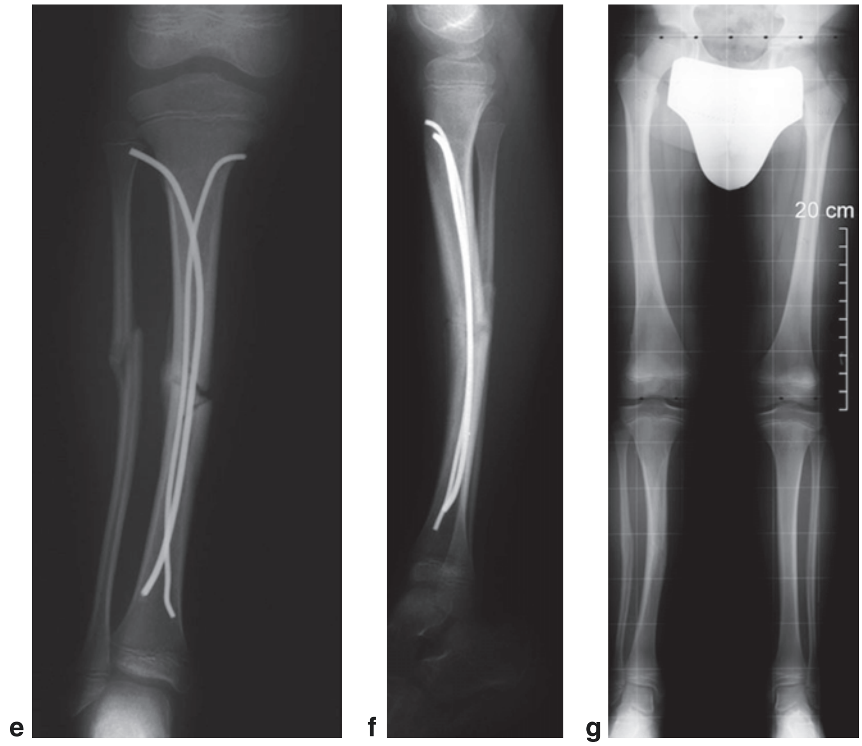

Fig. 20.3 *(cont.)* The *right tibia* was fixed during the same operative session. Antegrade FIN was performed on a fracture table using a lateral 3 mm titanium nail and a medial 2.5 mm titanium nail. In spite of postoperative immobilization in a cast boot to try to correct angular deformities, at 6 weeks there was a recurvatum angulation of 6° and a valgus angulation of 8° (**e**, **f**). Four years elapsed (the boy was then 15 years old): X-rays showed 15 mm lengthening of the *right lower limb*, and a valgus angulation of the *right leg* of 6° (**g**). Note: the asymmetric tibial construct was responsible for the angular deformities that failed to be detected intraoperatively: both nails should have been directed posteriorly to correct the recurvatum angulation and medially to correct the valgus angulation

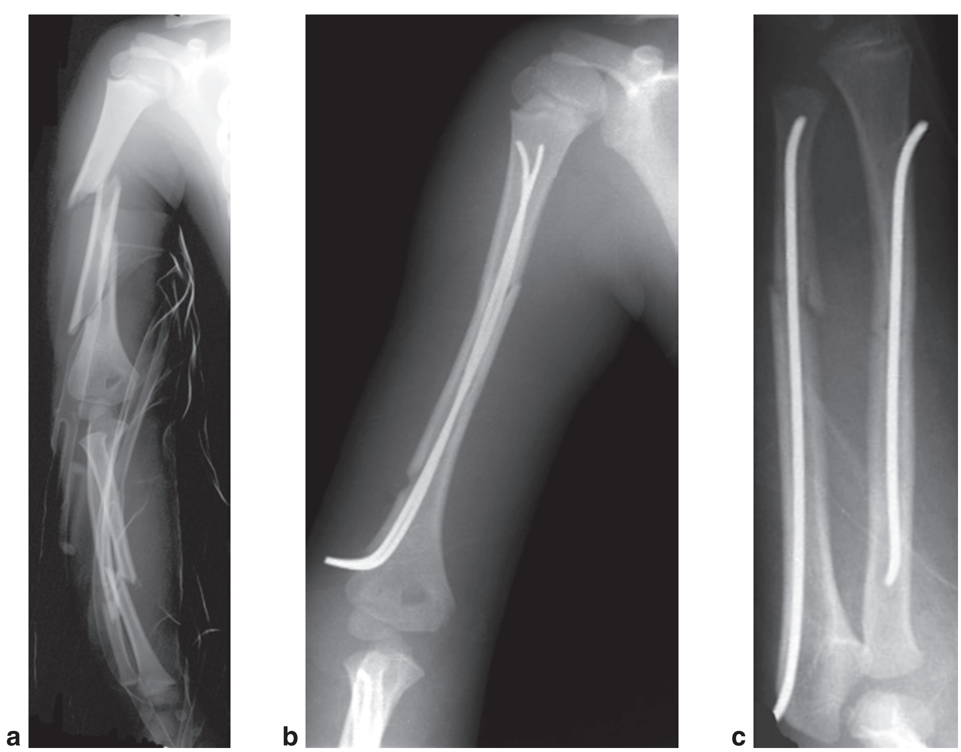

Fig. 20.4 A 7-year-old boy whose arm got caught in a spinning washing machine. The child had a double fracture of the *right humerus* with primary radial nerve palsy and fracture of both bones of the forearm (**a**). He was treated in emergency by unipolar retrograde FIN of the humerus using two 2.5 mm titanium nails, and surgical exploration of the radial nerve through the lateral biceps groove (**b**). Both bones of the forearm were managed with combined FIN using two 2.5 mm titanium nails (**c**)

ipsilateral hip dislocation, upper limb injury, or ipsilateral injuries of the femur and tibia. In any case, whatever the anatomic locations of long bone fractures, owing to the distinct advantages of FIN, the indications mentioned in the previous chapters for isolated fractures are significantly expanded in polytrauma (Fig. 20.5):

- Young age is no longer a contraindication, since monitoring is much easier without a cast.
- Nailing of upper limb fractures (including humerus) facilitates patient transfer to imaging units for postoperative monitoring (i.e., CT, echography, MRI).

Fig. 20.4 *(cont.)* The day following admission, a developing compartment syndrome was detected, which required forearm fasciotomy that was extended to the arm. Six months later, the humeral nails were removed (**d**) followed by the forearm nails (both bones) (**e**). Radial nerve palsy had resolved spontaneously, and the child had recovered full range of motion in the elbow and wrist. Note: excellent outcome with minimal surgical trauma

Fig. 20.5 An 8-year-old boy who fell from a height of 6 m on his *right side*. He had no neurovascular injuries in the *right upper limb* but he had multiple ipsilateral fractures: minimally displaced fracture of the neck of the humerus (**a**), severely displaced fracture of the radial neck, displaced fracture of both bones of the forearm, displaced fracture of the distal radius (**b**, **c**) and closed fracture of the *right femur* (**d**)

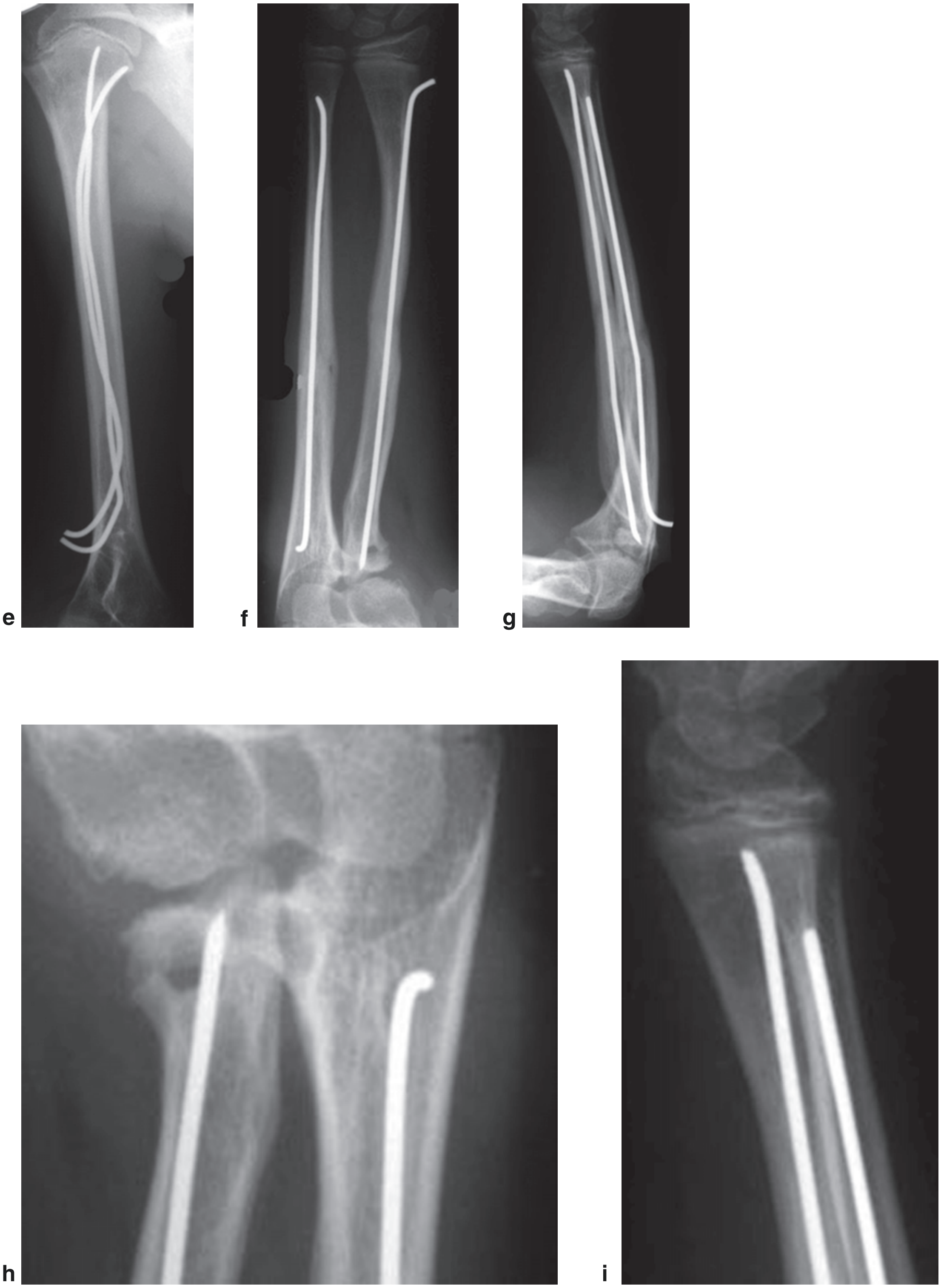

Fig. 20.5 *(cont.)* Surgical treatment consisted in: – retrograde FIN of the proximal humerus (**e**); closed combined FIN of radius and ulna for radial and ulnar shaft fractures (**f**, **g**); fracture of the radial neck was severely displaced and irreducible. An open approach was necessary both to reduce the radial neck fracture and to control insertion of the radial nail (for the diaphyseal fracture) into the proximal epiphysis (**h**); fracture of the distal radius was treated by simple reduction and immobilization in a short arm cast (**i**)

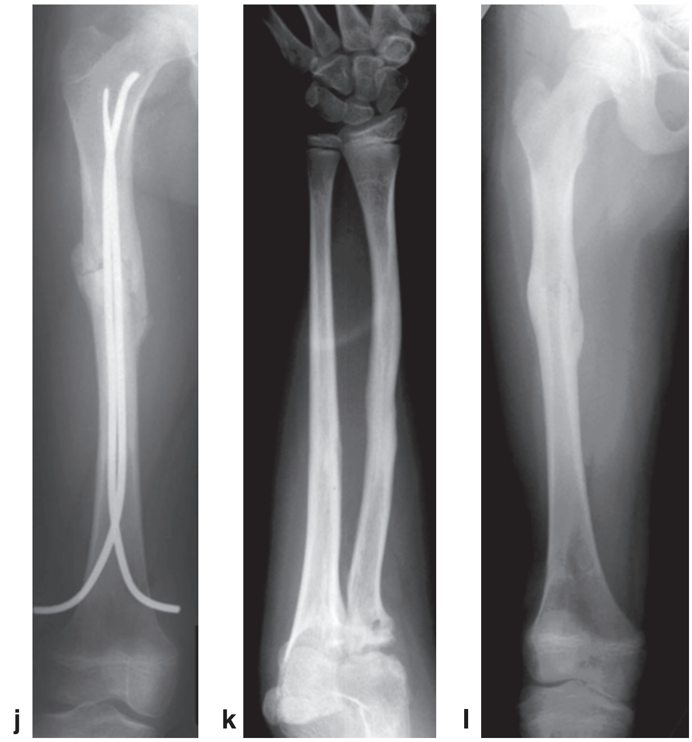

Fig. 20.5 *(cont.).* Bipolar retrograde FIN of the *right femur* (**j**). One year later, all fractures were united. The only complication was partial necrosis of the radial head (**k**, **l**). Note: the procedure was performed by a single surgeon (E. Gagneux) and lasted 4 h altogether (approx. 1 h per anatomic location. No blood transfusion was required)

- Detection of compartment syndrome, whether it be in the forearm or the lower leg, is much easier without a cast.

Patients with fractures of the upper limb and contralateral lower limb can be treated simultaneously by two surgical teams to reduce the operating time. The surgical trauma is minimized: small incisions, minimal iatrogenic muscle attrition, and limited blood loss owing to minimally invasive procedures. Many patients avoided blood transfusion, which would have likely been necessary with more invasive internal fixation methods.

On an average, independent of the anatomic region treated, an FIN procedure takes about 1 h, including prepping/draping.

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Part III

Other Indications

21 FIN and Bone Weakness

Jean-Marc Laville

Treatment of common fractures is not the only application that intramedullary nailing (FIN) can serve[1], it also proves most effective in treating pathological fractures and protecting a weakened bone area without adversely affecting the growth process. A description of the full range of FIN applications with their technical specificities and indications is given here.

The chief advantages of FIN in the involved areas include:

- Tremendous flexibility of the technique: it can accommodate most contingencies provided that basic principles of FIN are respected.
- Superior mechanical stability, which generally makes additional immobilization unnecessary.
- Possibility of crossing the growth plate with a minimal risk of epiphysiodesis.
- Percutaneous approach: it reduces the infection risk, and is not cosmetically disfiguring.
- Cost effectiveness.

21.1 Osteogenesis Imperfecta

Owing to bone growth, the wires must provide durable stabilization. This can be achieved with sliding FIN using two wires, one antegrade and one retrograde, which are anchored in the epiphyseal or apophyseal area.

Sliding FIN offers several key advantages:

- It accommodates any bone size.
- It allows stabilization of several realignment osteotomies in the same bone segment.
- Owing to the elastic properties of the wires, bone union can be achieved without any risk of cortical weakening. Actually, inherent elasticity of the wires stimulates bone formation, and allows mechanical loads to be evenly distributed in the bone.
- It helps protect the entire bone segment against recurrent fractures.
- It facilitates growth monitoring: as one end of each wire is anchored in the epiphysis or the apophysis, the wires slide in opposite directions, and their supportive function is maintained as long as overlap exceeds 30% of their overall length.

21.1.1 Technical Highlights

The wires are not anchored [2, 3] in the metaphyseal area but in the epiphyseal or apophyseal area (depending on the affected bone), one proximally and the other one distally. Their curved tips facilitate progression in the medullary canal. As the osteoinductive properties of titanium are not a requirement in this indication, stainless steel wires may be preferred. The wires are smoothly contoured in a manner that produces two opposing curves. Their trailing ends are bent into a U-curve and anchored in the epiphysis. Moderate contouring is recommended to avoid generating stresses that might cause splitting of the bone shaft during insertion. Similarly, optimal bending of the leading tip is essential to avoid misdirection and cortical violation, particularly, in extremely weak cortical bone (Figs. 21.1 and 21.2). The trailing end must have a perfect U-shape configuration with the two legs of the "U" strictly parallel to each other and long enough to provide a firm anchoring. Another option is to fashion the trailing end into a loop that is secured to the epiphyseal or apophyseal fibrocartilaginous tissue by passing a nonabsorbable suture several times through the loop. The diameter of the medullary canal is

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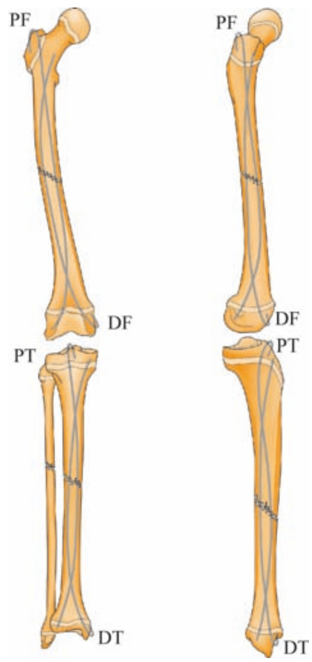


Fig. 21.1 Constructs used in the lower limb. *PF* proximal femoral wire; *DF* distal femoral wire; *PT* proximal tibial wire; *DT* distal tibial wire

measured intraoperatively using the image intensifier to determine the wire diameter. The wires can be advanced through the medullary canal to the opposite epiphysis without prior reaming. Small-diameter wires are generally used in these very young children (often less than 5 years): rarely more than 2 mm for the femur, and sometimes, only 1 mm for the upper extremity. In very narrow canals, one single wire may be initially inserted, the second one being inserted later on in the procedure. Realignment osteotomies require one or several stab incisions to advance the wire under visual control [4].

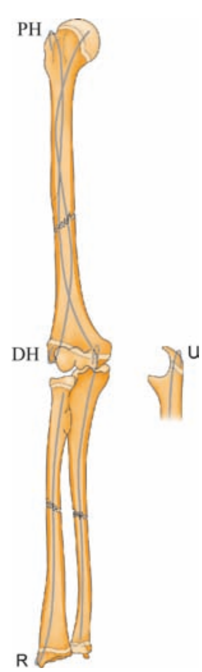


Fig. 21.2 Constructs used in the upper limb. *PH* proximal humeral wire; *DH* distal humeral wire; *R* radial wire; *U* ulnar wire

21.1.1.1 Femur

The proximal wire is inserted in an antegrade fashion either percutaneously, or through a small incision at the greater trochanter under image intensifier control. Due to the natural tendency to varus deformity of the femur, the concave side of this wire must face laterally so as to produce a valgus force. Then, a lateral parapatellar arthrotomy is performed to insert the distal wire through the lateral condyle or the intercondylar notch. The reason is that it is easier to orient the wire so that its concave side faces laterally and helps control the varus tendency. Where possible, this wire is rotated 180° upon reaching the proximal femur so that its tip can be advanced to the femoral neck. In patients with preoperative bone deformities, one or several mini incisions can be made in the lateral aspect of the femur to correct axial alignment by performing one or several closed wedge osteotomies, and to allow advancement of the wires under visual control. Then, the proximal wire is pushed into the lateral condyle, and its U-shaped end is carefully recessed into the greater trochanter using a graft pusher. Conversely, the distal wire is advanced to the femoral neck, and its distal U-shaped end is anchored in the femoral epiphysis (Fig. 21.3). As the varus deformity caused by the disease tends to recur, it may be useful to more sharply contour the antegrade wire so as to create a mild valgus angulation.

21.1.1.2 Tibia

The proximal wire is inserted through the arthrotomy performed for the distal femur or through an incision that is made anterior to the tibial spine. The wire is contoured so that its concave side faces laterally. The distal wire is inserted percutaneously through the medial malleolus. It is contoured so that its concave site faces medially. One or several subperiosteal osteotomies performed from an anterior approach are generally necessary to correct bone deformity and allow

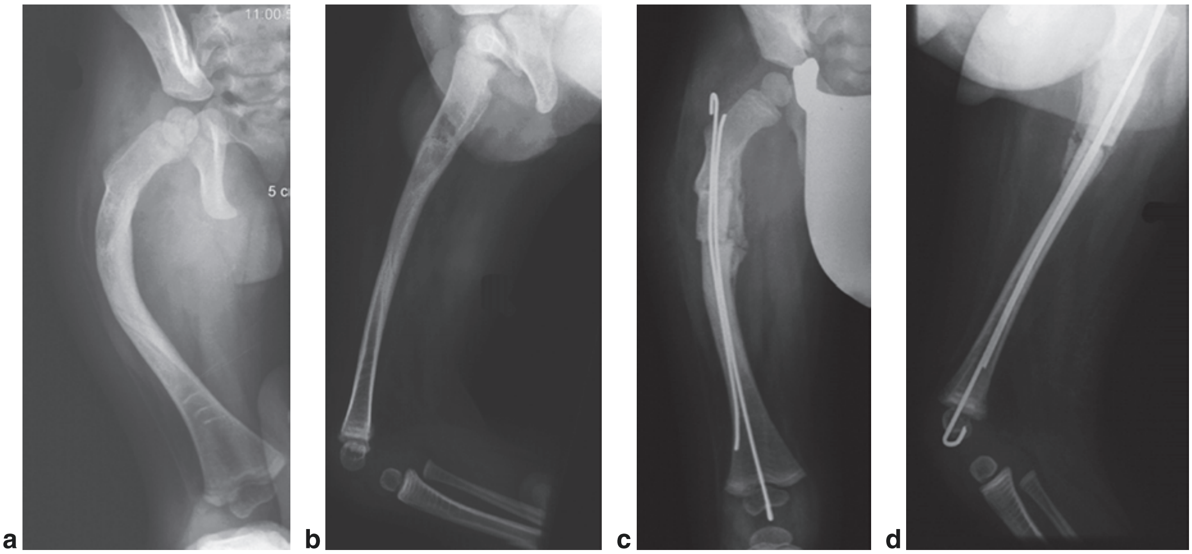


Fig. 21.3 A 2-year-old boy with osteogenesis imperfecta. Varus deformity of the *right femur* (**a**, **b**). Correction was achieved with double osteotomy and sliding flexible intramedullary nailing (FIN) using two 2 mm stainless steel wires **(c, d)**

advancement of the wire under visual control. Both wires are advanced to the opposite epiphyses. One U-shaped end (trailing end) is anchored just anterior to the tibial spine and the other one in the medial malleolus (Fig. 21.4). If it appears that the distal wire is too close to the skin surface, the construct may be reversed, and the wire inserted from an anterolateral approach – although it is technically more difficult due to the small size of the epiphysis.

21.1.1.3 Humerus

The antegrade proximal wire is inserted through the greater tuberosity. Contouring should create a long S-shape that allows to direct the wire toward the medial epicondyle. The retrograde wire is inserted through the lateral epicondyle on the lateral aspect of the humerus. Thanks to its long S-shape, it can be directed toward the head of the humerus. The U-shaped ends are anchored as previously described (Fig. 21.2).

21.1.1.4 Forearm

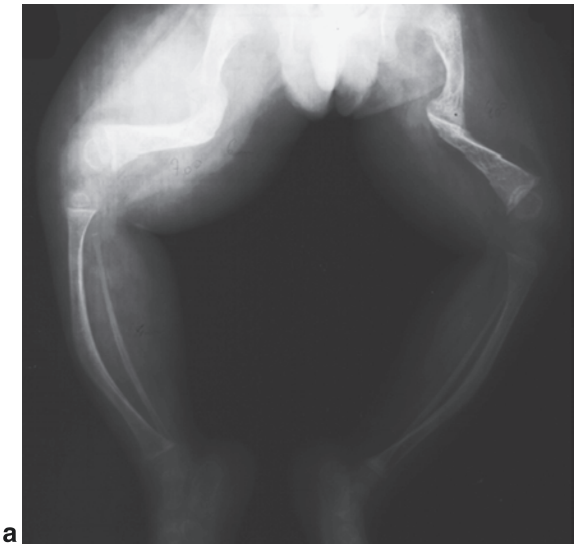
The technique is identical to that used for both bone forearm fractures, except for the transphyseal approach. Furthermore, the trailing end of the radial wire is anchored in the styloid process, and that of the ulnar wire in the olecranon. This facilitates access to the wires, and allows progressive sliding, should replacement be necessary (Fig. 21.3).

Fig. 21.4 A 2.5-year-old boy with osteogenesis imperfecta and flexion contraction of the tibia **(a)**. Osteotomy at the apex of the deformity and sliding FIN using two 1.5 mm stainless steel wires **(b)**

21.1.2 Clinical Experience

A French retrospective clinical study [5] was conducted to evaluate sliding FIN in 14 patients (36 procedures) with severe osteogenesis imperfecta (four girls, ten boys) (Fig. 21.5). Mean age at initial surgery was 4 years (range, 15 days–10 years), average number of procedures per patient was 2.5 (range, one to five procedures), and mean length of follow-up was 8 years (range, 1–12 years). Wires needed replacement in about 75% of the operated bone segments. Mean delay between initial surgery and surgical revision was 3 years for the femur and 3.5 years for the tibia. Functional behavior of the constructs was 100% satisfactory: no sliding failure was reported. In the absence of bone deformity, closed FIN was performed (Fig. 21.6).

a



b

Fig. 21.5 A 3-year-old boy with very severe osteogenesis imperfecta and bilateral bone deformities in both femur and tibia **(a)**. Osteotomies and sliding FINs were performed in the four bone segments; postoperative view (2 mm wires in femurs and 1.5 mm wires in tibias) **(b)**

21.1.3 Complications

Complications occurred in 25% of the cases:

- Four spontaneous refractures, where average residual overlap was only 30% (range, 0–45%) (Fig. 21.5d). The new fracture line ran obliquely between the wires, which still overlapped each other (Case 1).
- One refracture with the wires in situ was promoted by a varus angulation of 50° of the femur.
- In two cases, migration of the proximal femoral wire (PF) required surgical revision. This is why it is recommended to secure the “loop” to the cartilage with a nonabsorbable suture as an additional safety measure against implant migration and potential wire breakout (Fig. 21.7).
- One patient complained of discomfort due to prominence of a long trailing end at the distal femur.
- One nonunion.
- One bone shortening due to impaction of bone fragments.

With the exception of the nonunion, all other complications occurred in children aged more than 5 years. No infection was reported.

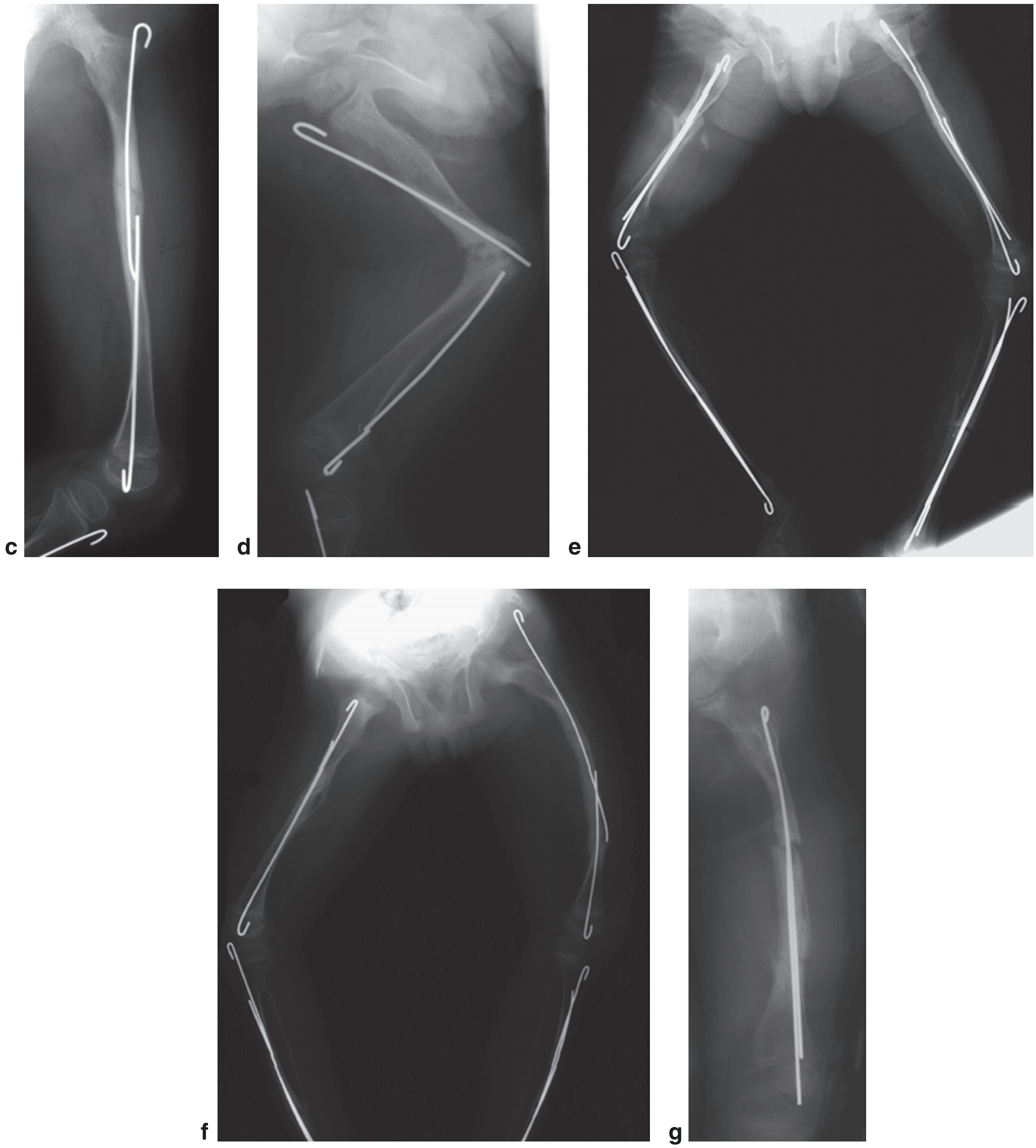


Fig. 21.5 *(cont.)* X-ray taken at the age of 6 years: there was such significant sliding in the *left femur* that the residual overlap was only 14% of the overall length (**c**). At that time, the *right femur* fractured due to insufficient protection (**d**). Surgical revision was performed with bilateral replacement of the wires in both the femur and the tibia (**e**). When the child was 8 years old, sliding ended up in migration of a wire in the *left femur*, causing varus angulation (**f**). Re-revision consisted in double femoral osteotomy and replacement of the wires (2.5 mm) **(g)**

Fig. 21.6 A 7-year-old girl with moderate osteogenesis imperfecta and a subtrochanteric fracture which was healing well. Sliding FIN was performed using two 2 mm wires

21.1.4 Indications

In severe forms of osteogenesis imperfecta, early surgical treatment, even in infants, decreases the incidence of fractures and delays the development of bone deformities [6–8], even though the recent introduction of biphosphonates seems to improve the prognosis of this disease. However, the use of small-diameter telescopic intramedullary nails [4], particularly in children below 5 years of age [9, 10], is associated with a significantly higher complication rate. As a matter of fact, wire rigidity is detrimental to the development of cortical bone because the implant takes most of the mechanical load. This is why wire breakout is not rare. In contrast, the vast majority of complications associated with sliding FIN are seen in children aged more than 5 years (i.e., refracture, implant migration, and recurrent deformity). Therefore, sliding FIN should be preferably used in children under five [8]. Analysis of medical records suggests that the incidence of refracture might be decreased by prophylactic replacement of the wires as soon as they form an angle of nearly 30°, or overlap is close to 30% of their length. There are two additional indications, which are quite close to that for osteogenesis imperfecta: osteoporosis and Larsen syndrome (Fig. 21.7).

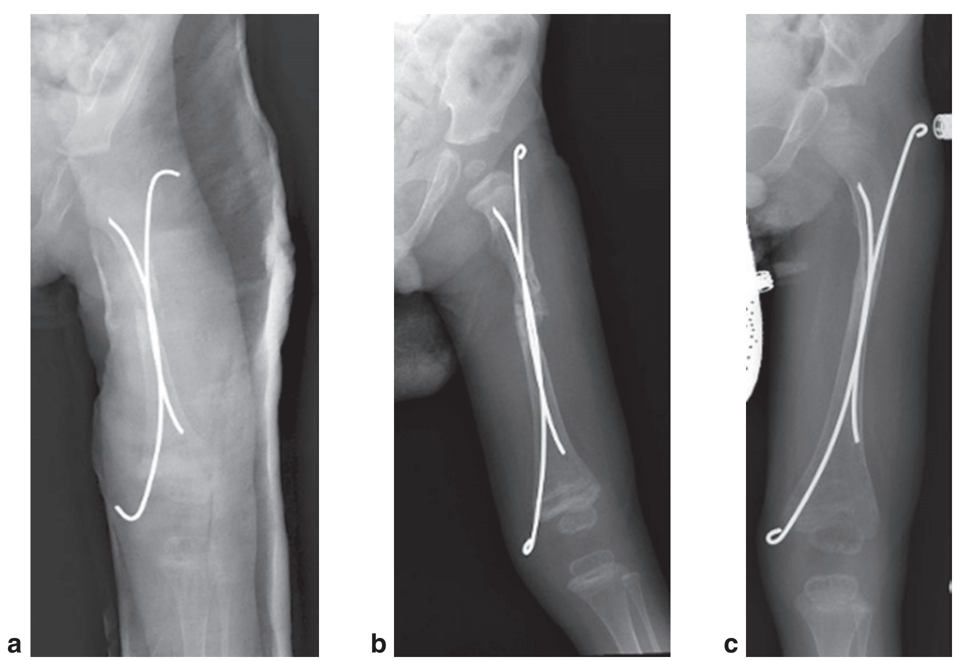


Fig. 21.7 An 18-month-old male with Larsen syndrome and recurrent fractures of the *left femur*. (**a**) A first sliding FIN was performed using two 2 mm stainless steel wires; (**b**) later on, the wires broke through the skin and surgical revision was mandatory. The trailing ends were fashioned into loops that were sutured to the fibrocartilaginous tissue; (**c**) solid union took place and the growth process continued. At the age of 2 years, the wires were still well tolerated (courtesy of P. Lascombes, P. Journeau)

21.2 Cerebral Palsy and Neuromuscular Diseases

The specific problems associated with cerebral palsy (i.e., spasticity, sensory disorders, difficulty in expressing pain) do not speak in favor of cast immobilization due to the increased risk of pressure sores. A fractured limb in a nonambulatory quadriplegic child may preclude the use of his/her wheelchair or molded seat and cause child's regression. These are enough reasons to prefer internal fixation in these patients. However, the higher risk of infection is an important factor that must be taken into account when invasive treatment methods are considered. Internal fixation techniques other than FIN are unsuitable for these cases, particularly screw plates, which carry a high risk of refracture above and/or below the implant. Being left in situ, the fixation device is supposed to act as a supportive frame, and as such, reduce the likelihood of recurrent fractures and prevent severe displacement in case of refracture. FIN meets all these requirements: it is simple, minimally invasive, allows early mobilization, provides long-term protection, and facilitates monitoring since cast immobilization is unnecessary.

21.2.1 Technical Highlights

The main goal of FIN in this patient population is twofold: provide early stabilization and long-term protection. Due to high spasticity, it is recommended to select the largest nails that can be accommodated: 4 mm nails are often used in children aged 10 years or more for the femur. In femoral shaft fractures, standard retrograde FIN using medial and lateral approaches to the distal metaphysis can be performed. At the end of the procedure, the nail ends are trimmed close to the bone surface and fully recessed using a graft pusher (Fig. 21.8). There are several reasons for this: high risk of implant migration, skin irritation, which may cause deep infection that may not be diagnosed immediately, and the fact that the nails are intended to be left in place and serve as a permanent frame.

As secondary distal femoral (DF) metaphyseal fractures often occur more or less spontaneously, preventive measures should be taken whenever possible. If a femoral shaft fracture is treated by FIN, the surgeon must manage to also use the construct for protection of the distal metaphysis. One way to do it is to insert antegrade subtrochanteric nails into the distal epiphysis, being aware of the nonnegligible risk of subtrochanteric fracture at the entry hole. Therefore, the nails may be inserted either through the greater trochanter or through the distal epiphysis using a condylar approach, on the condition that both nail ends be fully countersunk.

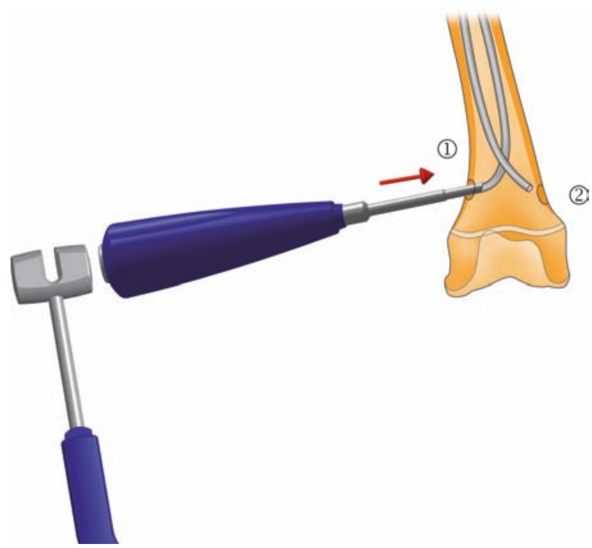


Fig. 21.8 *1*. Nail is fully recessed using a graft pusher. *2*. Nail end is countersunk

21.2.2 Indications

21.2.2.1 Cerebral Palsy

In children with cerebral palsy, all diaphyseal and metaphyseal can be treated by FIN, either antegrade, retrograde, or combined according to each individual situation, taking into account the high risk of refracture in these brittle bones. In patients with significant remaining growth potential, sliding FIN with countersunk nail ends is a valuable option.

If a proximal femoral fracture occurs below an existing fixation plate (e.g., osteotomy plate in the hip), a retrograde FIN with the nails passing through the tiny gaps available in the screw holes (at the bone-screw interface), can provide adequate stabilization of the fracture (Fig. 21.9).

21.2.2.2 Neuromuscular Diseases

Patients with neuromuscular diseases, myopathy, or spinal amyotrophy are much less prone to fractures. But when a fracture occurs, particularly in the lower

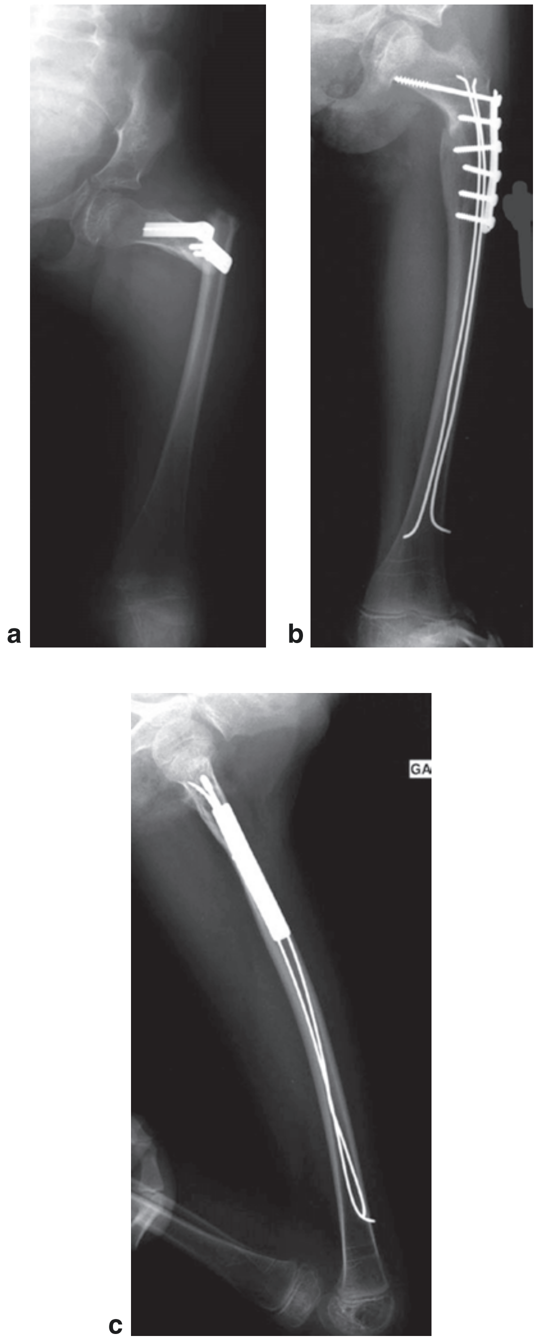


Fig. 21.9 A 9-year-old girl with cerebral palsy who had undergone varus osteotomy of the proximal femur 1 year earlier. Fracture occurred at the distal plate hole (**a**). Again, a screw plate was used and was associated with bipolar retrograde FIN using two 1.5 mm stainless steel nails. Bone union was achieved (**b**, **c**). At 7-year follow-up, no new femoral fracture had occurred (courtesy of P. Lascombes)

limb, it is at a high risk of developing potentially dreadful complications due to the recumbent position. Because of the risk of functional regression, which is highly undesirable in these patients, nonoperative treatment is rarely used. A dynamic therapy like FIN is far more appropriate. The technique is identical to that used in children with cerebral palsy.

21.3 Benign Bone Tumors

Selection of the appropriate treatment method for a benign bone tumor is based on:

- Diagnosis: as it is essential to make sure that the lesion is benign, after all routine imaging studies, surgical biopsy is often performed for confirmation. If the benign tumor has been revealed by a fracture even located in the lower limb (e.g., femur), it is even more important to use standard nonoperative treatment or traction until diagnosis is confirmed (Fig. 21.10).
- The surgeon should select the treatment method that best meets the needs of the individual patient [11, 12]. Several treatment methods are available: curettage or subperiosteal resection and bone grafting, corticoid or bone marrow injections, and even tumor embolization. However, none of them can

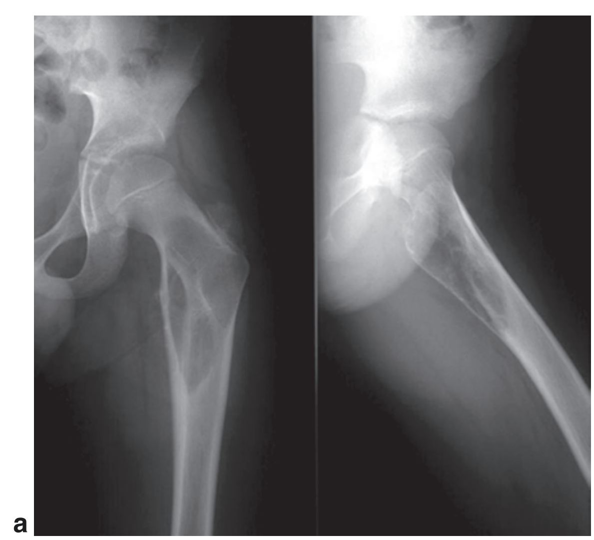


Fig. 21.10 An 11-year-old boy who complained of pain in the femoral neck: the lesion revealed by X-rays was mistakenly diagnosed as a unicameral bone cyst of the proximal femur (**a**)

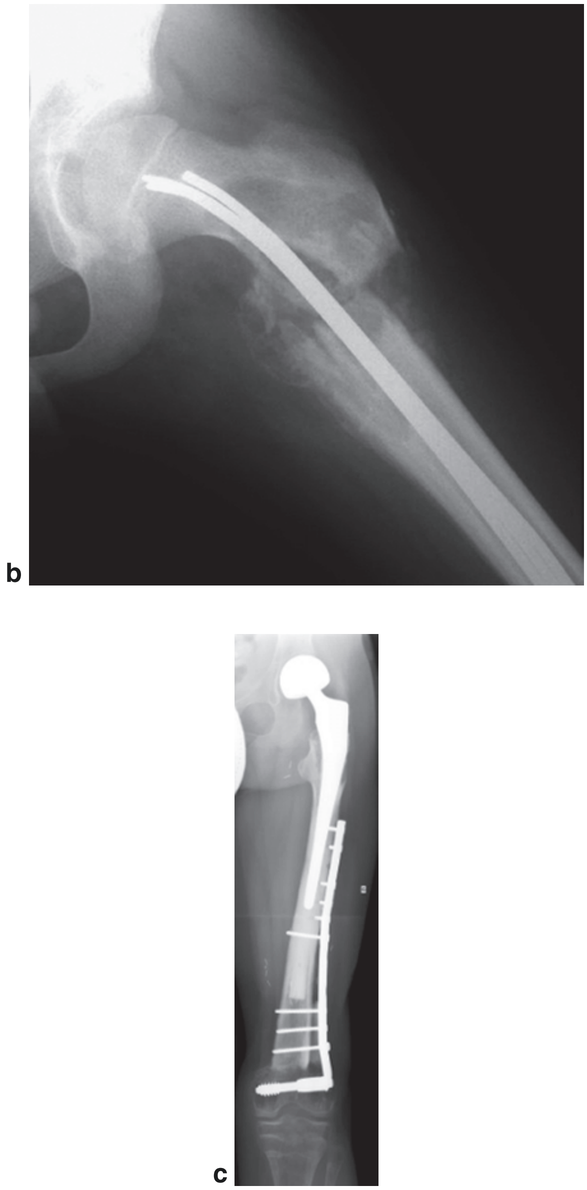


Fig. 21.10 *(cont.)* He then sustained a fracture in a simple fall which was treated by retrograde FIN (**b**). However, the radiographic appearance of the cyst prompted the surgeon to perform a bone biopsy which revealed osteosarcoma. A chemical therapy was started as per protocol OS 94. Subsequently, the tumor and the internal fixation device were removed en bloc (i.e., subtotal resection of the femur). The proximal femur was reconstructed using a hip prosthesis and bone allografts. Result at 2-year follow-up (**c**) (courtesy of P. Lascombes). Note: a pathological fracture should never be treated by internal fixation without a biopsy-established diagnosis

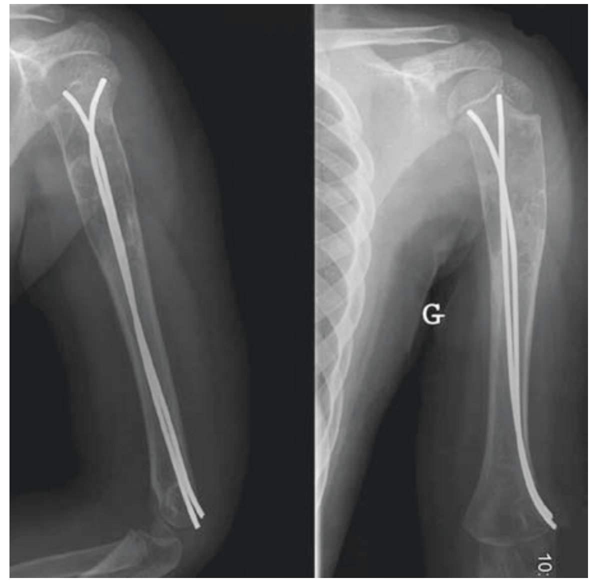


Fig. 21.11 Essential bone cyst of the proximal humerus in a 6-year-old boy: retrograde FIN (two 2 mm stainless steel nails) was performed to protect against fracture

prevent pathological fractures as long as the tumor is not cured.

- Therefore, the question is how to minimize this associated risk of fracture. FIN offers the advantage of providing immediate stabilization and bone protection against potential fractures.

21.3.1 Technical Highlights

The technique is identical to that used for treatment of common fractures (Fig. 21.11), but here, growth plate crossing is mandatory if the tumor is located in the metaphysis (Case 2). With growth, the femoral head gradually slides along the nails, which become too short and loose their protective capability, which requires that nails are replaced with longer ones whenever necessary. Therefore, care should be taken to make the distal ends of the nails easily accessible for later removal, but not too close to the skin surface to avoid the risk of subcutaneous tissue irritation. For this reason, it is advisable to insert the nails 40–50 mm proximal to the DF physis so that they lie deep to the vastus medialis and lateralis. The body often produces a bursa as a tissue response to the implant. This phenomenon should be explained both to the child and the family. Sliding FIN is also a good option for young children if there is a need for protection of a diaphyseal fracture.

21.3.2 Indications

This method is the treatment of choice in a weight-bearing bone segment, whether or not the tumor is associated with a fracture. In nonweight bearing bone segments, a wide selection of treatment options is available, including FIN; it all depends on the quality of bone stock.

21.3.2.1 Unicameral Bone Cyst

FIN offers the advantage of providing immediate stabilization and bone protection against new fractures, while allowing aspiration of the cyst contents through the medullary canal [13]. In spite of the frequent need for nail replacement during the growth period, FIN seems to be effective in treating this type of bone tumor, with similar results to other currently available treatments [14–18].

Healing time of fractures after unicameral bone cyst is identical. The nails need to be replaced during the growth process. In more than 50% of the cases, the cysts heal completely and allow removal of the nails. In all other cases, the nails are left in situ as a safety measure, even though the bone cyst seems to reach a steady state (Case 3).

Fig. 21.12 FIN construct for treatment of a pathological fracture after fibrous dysplasia of the tibia

21.3.2.2 Other Applications

FIN is, indeed, an attractive solution to protect against the likelihood of fracture, although not having a curative effect on the bone tumor. It can also be proposed for the treatment of other benign tumors such as fibrous dysplasia (Fig. 21.12) [19], Langerhans cell histiocytosis, where grafting is not desired, lymphangiomatosis, and osseous angioma [20].

21.4 Conclusion

FIN is a flexible internal fixation technique, which addresses a variety of specific requirements of the growing child. One of the most attractive applications involves treatment of pathological fractures. Sliding FIN for the treatment of osteogenesis imperfecta is also of great value in young children [21–23].

21.5 Case reports

21.5.1 Case 1

A young female with osteogenesis imperfecta. At 2 years, she fractured her left femur for the third time (a). At 3.5 years, a fourth fracture of the left femur was treated by combined FIN (b, c): an antegrade wire inserted through the greater trochanter and a retrograde wire inserted through the medial condyle (1.5 mm stainless steel wires). At the age of 5 years, sliding of both wires resulting from bone growth was patent (d, e). At the age of 9 years, bone growth was still taking place. The two wires overlapped each other by 90 mm (f). At the age of 11 years, an oblique fracture occurred between the wires (g). An on-the-spot surgery was performed: combined FIN using two 2.5 mm wires. But the wires were too thin, and one of them threatened to break through the skin at the knee (h). Internal fixation was revised to epiphyseal retrograde FIN using two 4 mm Nancy® nails (i). No new fracture occurred, and the patient is now reaching the end of growth still protected by her three nails (j)(courtesy of P. Lascombes) (Fig. 21.13).

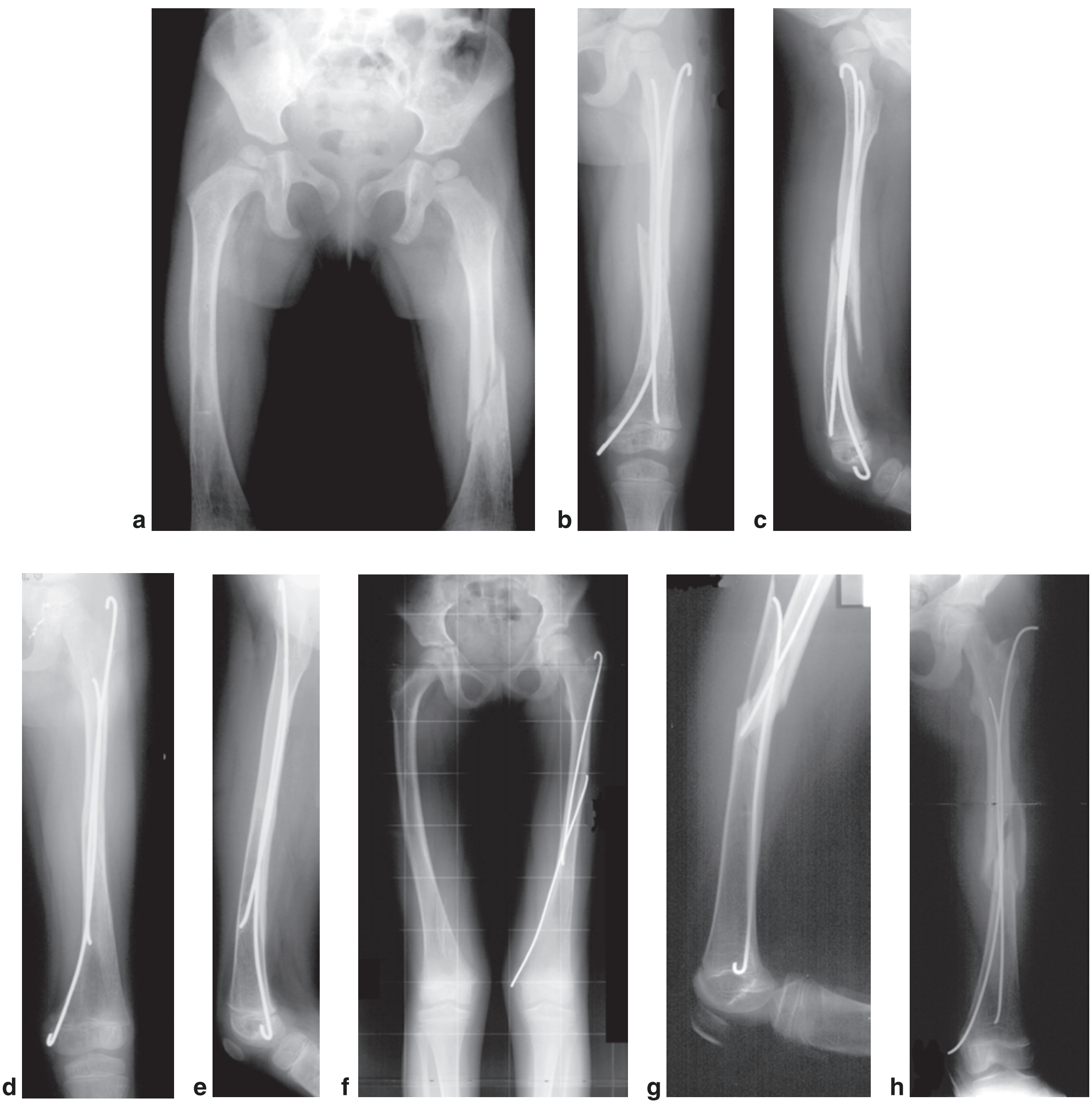
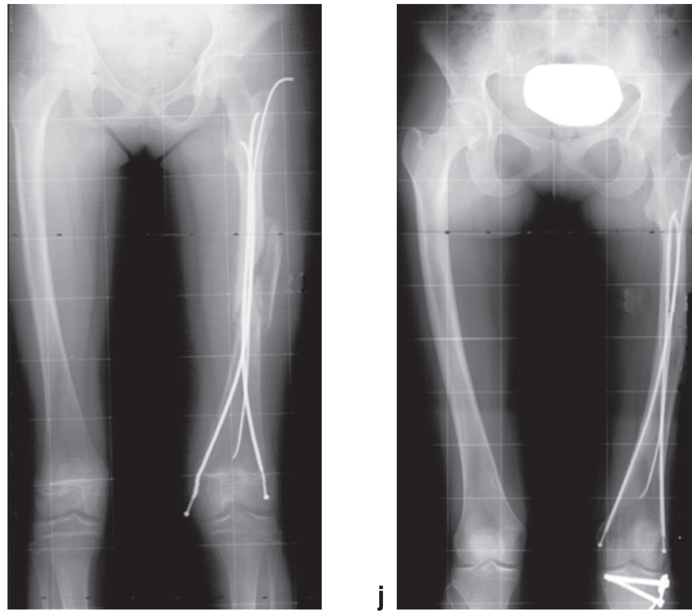


Fig. 21.13 Case 1

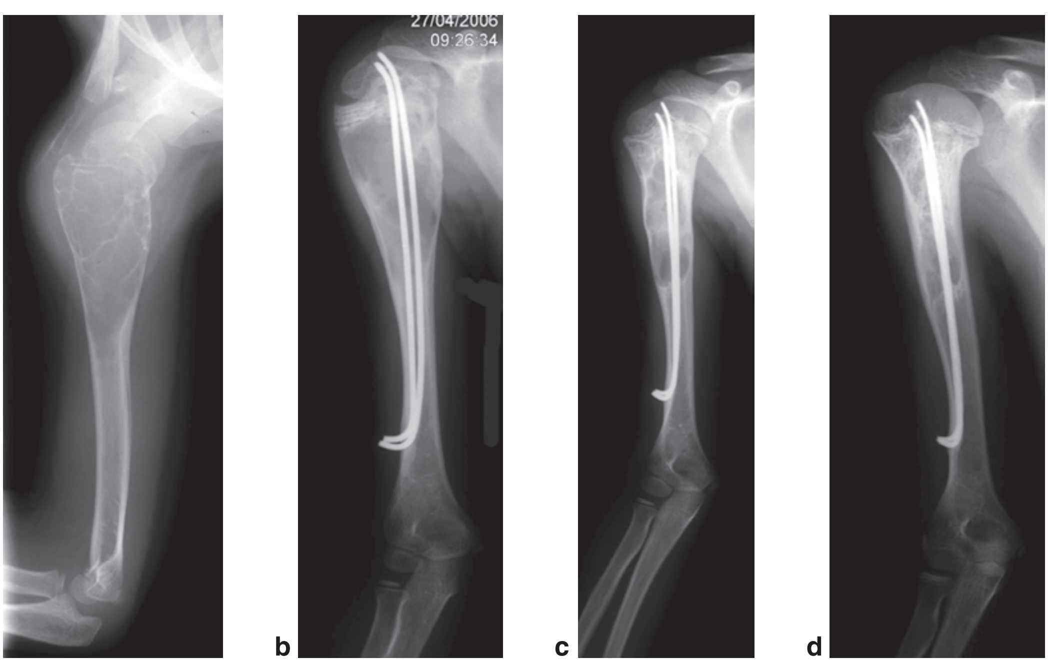


i j

Fig. 21.13 *(cont.)* Case 1

21.5.2 Case 2

A 6-year-old girl with a large bone cyst located in the proximal humerus. As an aneurysmal bone cyst was initially suspected, histological confirmation was requested (a). Eight months later, after two corticoid injections, a fracture occurred, which was treated by retrograde FIN (b). One year later, gradual healing of the bone cyst was noted (c). It was confirmed later on at the age of 9, but unfortunately, at that time, X-rays showed evidence of epiphysiodesis of the proximal humerus (d). When the girl was 16, she wanted to have the 120 mm shortening of her affected arm corrected. Gradual lengthening of the arm was proposed (e) and bone union was achieved within less than 1 year (f) (courtesy of P. Lascombes) (Fig. 21.14).



a b c d

Fig. 21.14 Case 2

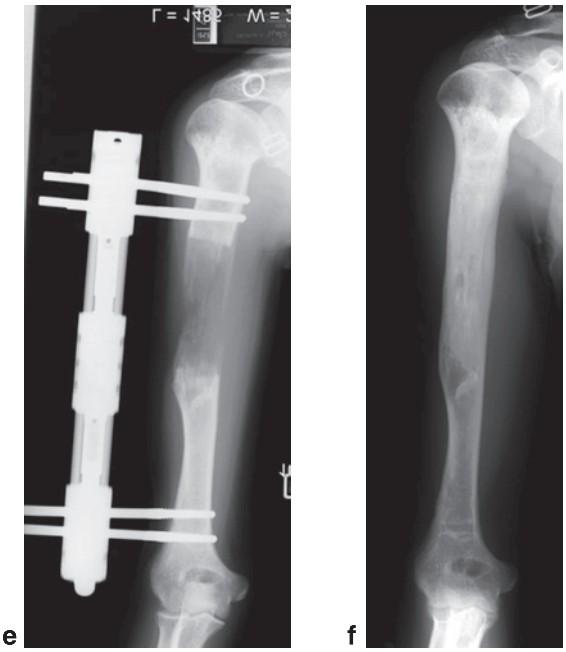


Fig. 21.14 *(cont.)* Case 2

e f

21.5.3 Case 3

An 8-year-old boy with a bone cyst of the right proximal femur (a) confirmed by MRI (b) and aspiration cytology. Prophylactic FIN was performed using two 3 mm Nancy® titanium nails (c, d). Sixteen months later, with growth of the femoral neck, the nails were pushed toward the bone cyst, which was still active after two in situ injections of corticoids and one injection of bone marrow. Furthermore, radiolucency was visible on radiographs in the lateral cortex of the midshaft of the femur (e). Biopsy revealed titanium-induced granuloma, which required replacement of the nails with 3.5 mm stainless steel nails (f). One year later, at the age of 11 years, the upper ends of the nails got close to the bone cyst, which became active again after showing signs of regression (g). Again, the nails were replaced, and the distal ends were made more soft-tissue friendly (h). At the age of 12 years, the boy sustained an undisplaced fracture in the bone cyst area resulting from high-energy trauma, which proved that the nails had effectively protected the femur (i). When the boy was 14, spontaneous regression of the bone cyst prompted us to remove the nails. Actually, only one nail could be removed, as the other one was embedded in the femoral bone. It was therefore left in situ, and the untreated leg was found to be shorter by 15 mm (j). At the age of 15 years, the boy again fractured his femur during a motorcycle accident, below the cyst, which was incompletely healed. It was a complex fracture with a third fragment, the femur had shortened, the nail was buckled, and the medullary canal was narrow (k). The nail was simply straightened under general anesthesia and the fracture was reduced. Postoperative course was uneventful, and at 16 years, the boy had a correctly aligned femur, no leg length discrepancy, and his well fixed femoral nail was left in place (l) (courtesy of P. Lascombes) (Fig. 21.15).

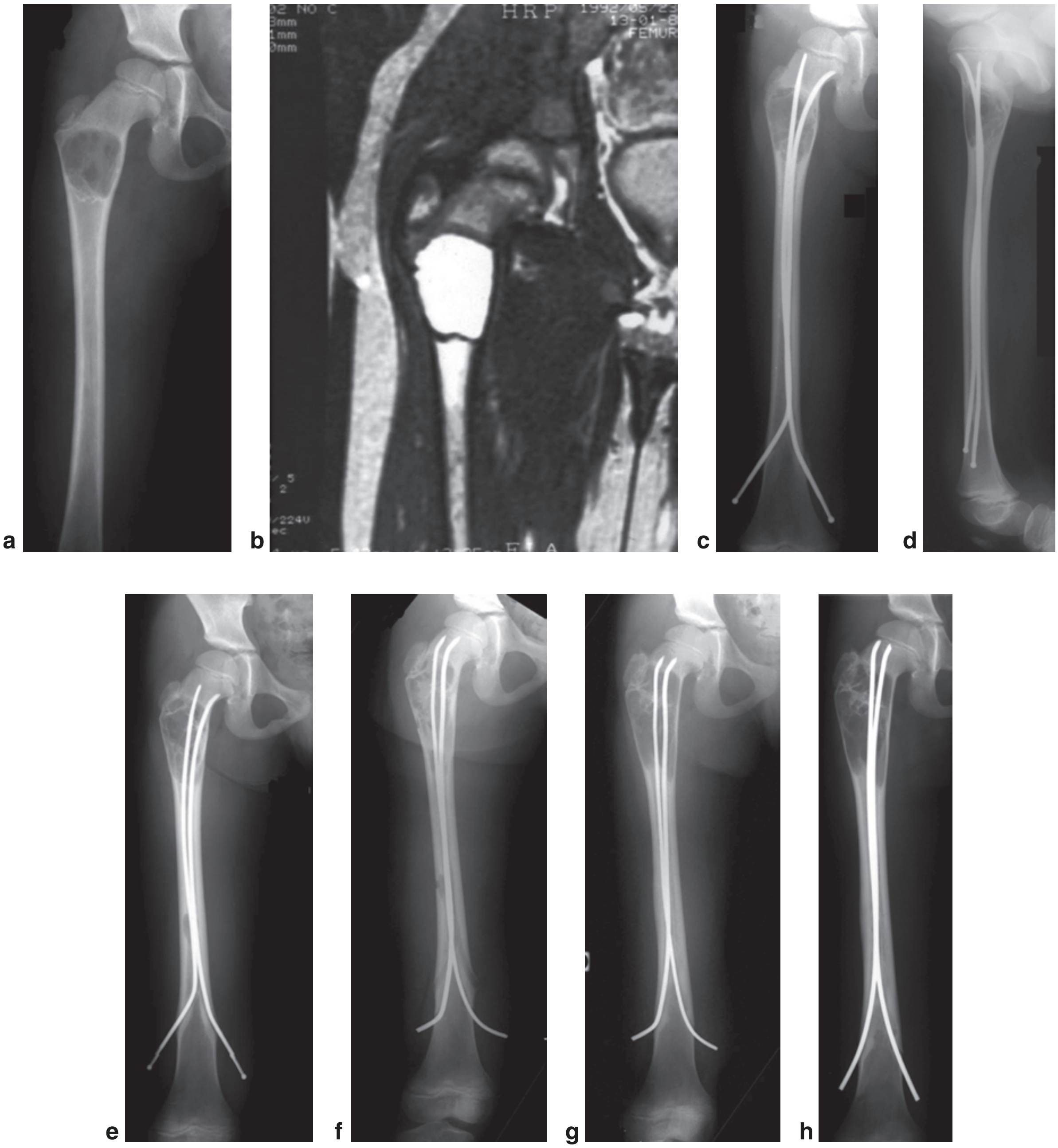


Fig. 21.15 Case 3

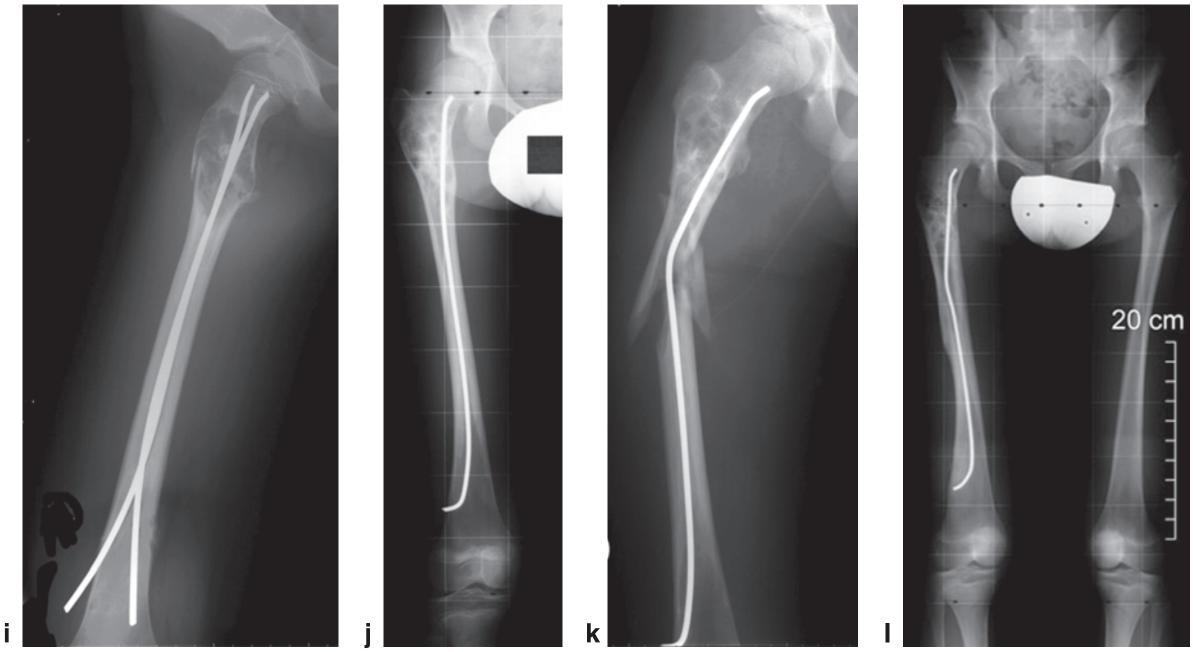


Fig. 21.15 *(cont.)* Case 3

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22 FIN in Ilizarov Bone Lengthening

Dimitri Popkov

22.1 Introduction

In view of the good results achieved in our experimental series, a clinical study was initiated in June 2001. For the very first time, a method combining the Ilizarov technique with FIN (flexible intramedullary nailing) was used for femoral lengthening in an adolescent with congenital limb length discrepancy (LLD). In the first ten patients, the free ends of the intramedullary nails were secured to the rings of the Ilizarov fixator. Since then, our technique has greatly improved and is now an important component in the therapeutic armamentarium of pediatric orthopedics.

22.2 Surgical Technique

The first surgical step is standard: application of the external fixator, followed by a percutaneous osteotomy that preserves integrity of the periosteum and intramedullary vessels [1, 2] (Fig. 22.1).

The second step is FIN: two 10–20 mm longitudinal incisions are made in the metaphyseal region. Two entry holes are created with an awl in an oblique direction toward the osteotomy within 20–30 mm of the growth plate. In monofocal femoral lengthening, the nails are inserted retrograde through the distal metaphysis. Tibial nails are inserted antegrade through the proximal metaphysis. Humeral nails are inserted retrograde from a distal approach through the lateral supra-epicondylar incision.

FIN uses two 1.5–2.0 mm stainless steel nails, which are contoured to achieve a curvature of 40–50°. Nail tips are tapered and prebent (30–40°) over a length of 2–3 mm. Nail contouring is intended to provide a final construct with two opposing curves. Both nails lie in the same plane within the bone, thus replicating the strong, elastic geometric system of a diaphyseal fracture. The main difference in the nails used in fractured bones is the smaller diameter.

Nails must be carefully advanced one at a time as far as the osteotomy site, pushed across the site, and then directed to the opposite metaphysis. The apexes of the curves must be located in a diaphyseal area close to the osteotomy so that, proximally, the nails intersect above the osteotomy. As lengthening progresses, the apexes slowly move to finally reach the regenerated bone area at the end of the lengthening process (Fig. 22.2).

In a straight bone segment, the nails must have symmetric curves, whereas in patients with a deformed bone, one of the nails may need sharper bending to exert a constant force that assists in gradually correcting the angular deformity during lengthening. Alternatively, the surgeon may reorient the nails by rotating them so that their concavities are oriented toward the convexity of the deformity (Fig. 22.3).

The free ends (trailing ends) of the nails are sharply bent (more than 90°) to prevent migration during distraction. Then, they are trimmed as usual, leaving approximately 5–10 mm proud of the bone surface. The skin is closed in one layer.

It is also possible to associate bifocal lengthening with FIN (Fig. 22.4). In this case, bipolar nailing is more appropriate. For instance, in the humerus, one nail is inserted antegrade through the proximal metaphysis, and the second nail is inserted retrograde from a distal approach through the lateral supra-epicondylar incision in the elbow. During lengthening, the nails slide in opposite directions, as in the technique used for treatment of osteogenesis imperfecta. Once the external fixator is removed, both regenerates are

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DOI: 10.1007/978-3-642-03031-4_22, © Springer-Verlag Berlin Heidelberg 2010

a b c d e f g

Fig. 22.1 A 15-year-old girl with congenital limb length discrepancy (LLD). Preoperative view (**a**); (**b**) X-ray taken after 7 days of lengthening; (**c**) X-ray taken after 30 days of lengthening; (**d**) multiple segment automatic high-frequency lengthening; (**e**) X-ray taken on the last day of the fixation period; (**f**) AP view after removal of the external fixator. Amount of lengthening was 45 mm in the femur and 20 mm in the tibia. Total healing index (HI) for the two bone segments was 12.9 d/cm; (**g**) 4 months after removal of the external fixator and before removal of the nails

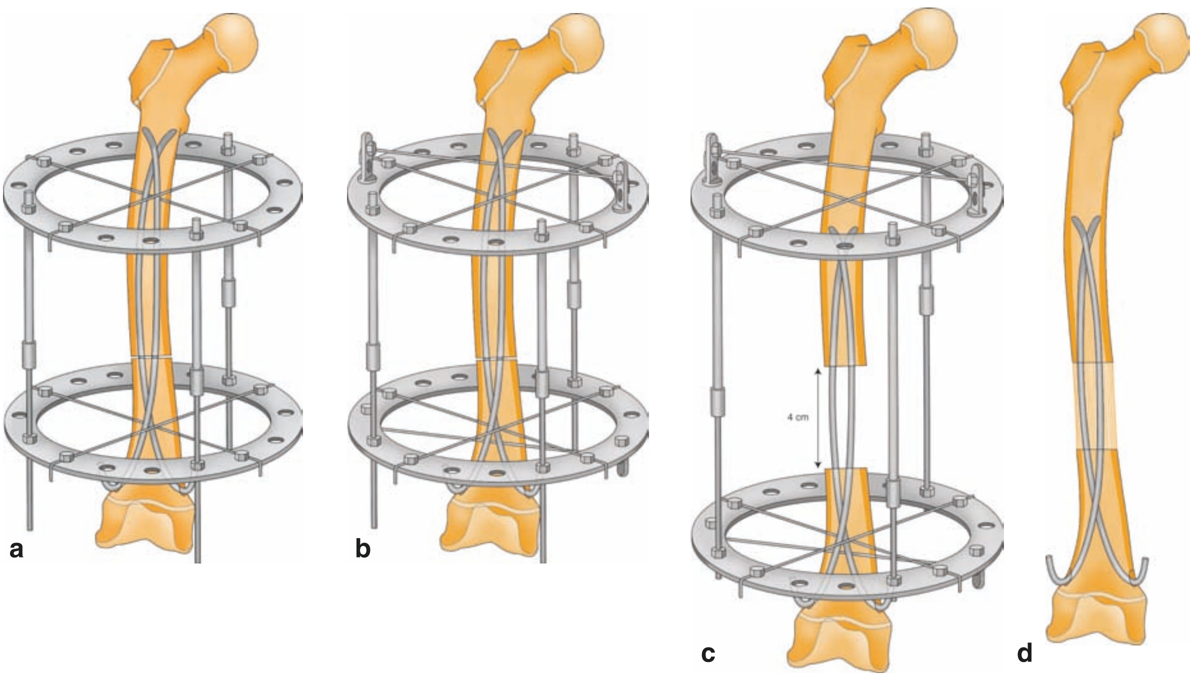

Fig. 22.2 Surgical technique: placement of the two Ilizarov rings, osteoclasis of the femur, nail contouring (approx. 40–50°) (**a**). Both nails are advanced retrograde up the medullary canal. The maximum of the curve is located proximal to the site of osteoclasis. Distal ends (trailing ends) of the nails are bent. Additional wires may be inserted through the Ilizarov rings (**b**). With lengthening, the nails are pulled by the distal fragment and slowly slide within the medullary canal (**c**). The external fixator can be removed as soon as the regenerate seems to have consolidated (**d**)

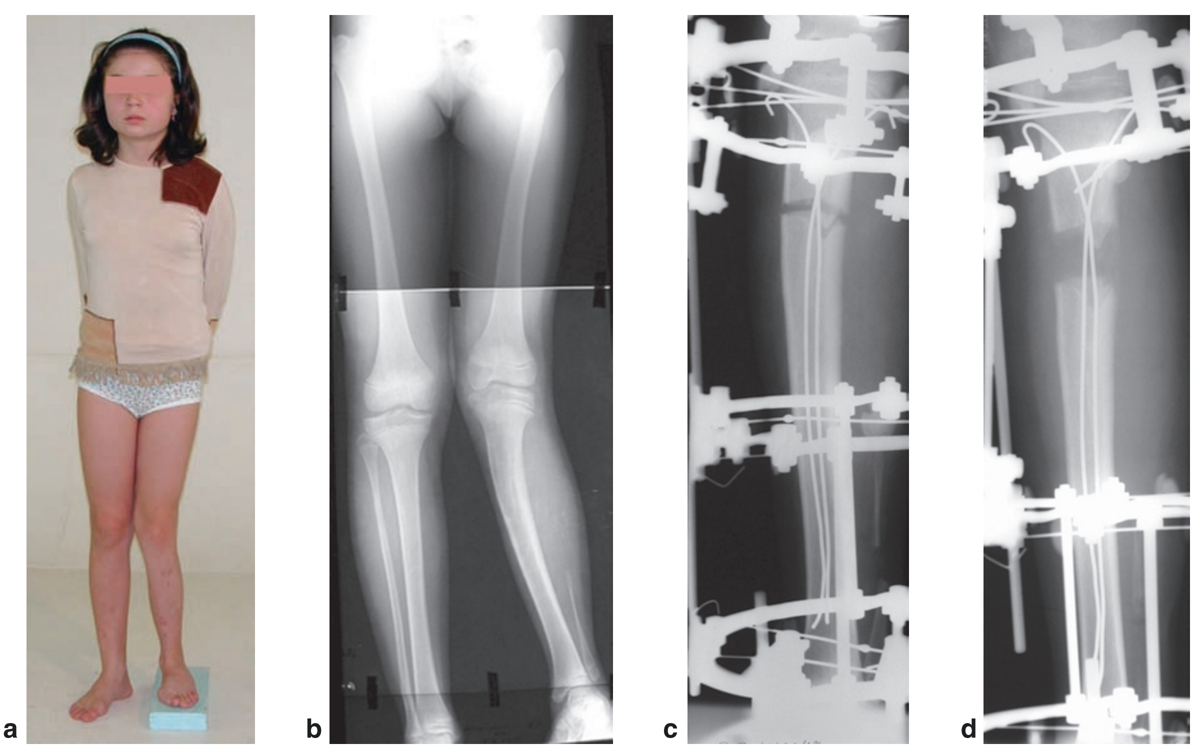

Fig. 22.3 A 12-year-old girl with congenital LLD before surgery (**a**). AP view of the lower limbs before surgical treatment. Note the genu valgum and the combined valgus-procurvatum angulation of the proximal third of the tibia (**b**); (**c**) AP view of the left tibia after 10 days of lengthening. The tibial deformity was still present; (**d**) AP view of the *left tibia* after 30 days of lengthening. Anatomic axis was restored in the coronal plane

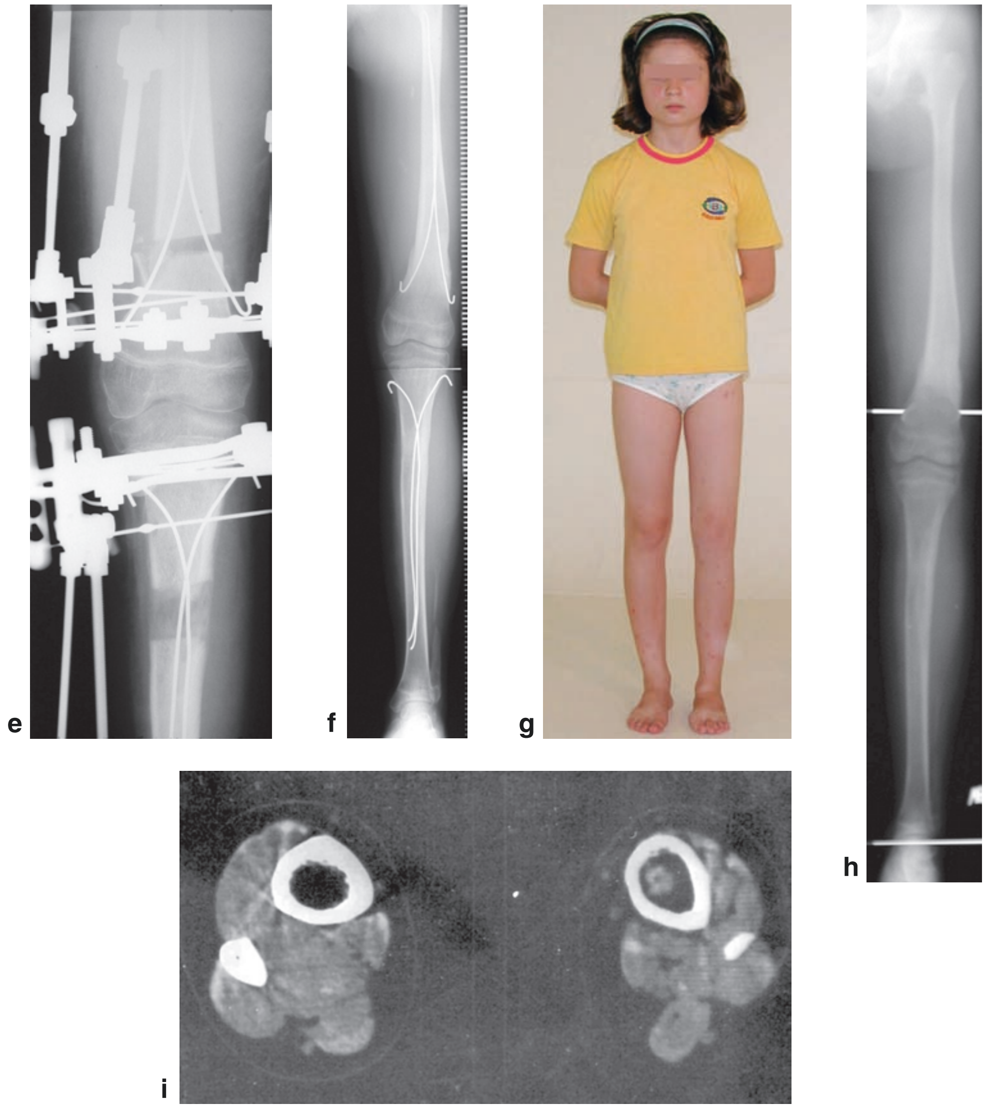

Fig. 22.3 (*cont.*) (**e**) X-ray taken at initiation of femoral lengthening (**i**) on the fifth day of the fixation period for tibia; (**f**) AP view of the lower limb 2 months after removal of the external fixator; (**g**) 4 months after removal of the femoral external fixator and 15 days after removal of intramedullary nails; (**h**) AP view of the lower limb after removal of the nails. CT image of the middle third of the unaffected right tibia and lengthened left tibia. Note extensive new-bone formation in the medullary canal on the side of the intramedullary nail (**i**)

buttressed by at least one intramedullary nail that has been properly contoured and oriented to resist secondary angular deformity. For instance, in bifocal femoral lengthening, the concave side of the proximal nail should face laterally to resist varus forces, and the concave side of the distal nail should face medially to resist the tendency of the distal femur to deviate into valgus.

In forearm lengthening, we normally use a constrained construct: a radial nail with its concave side facing the ulna, and an ulnar nail with its concave side facing the radius (Fig. 22.5). The radial nail is always inserted retrograde through a 15–20 mm incision centered over the distal physis (after the neighboring nerves and superficial veins have been retracted), and the ulnar nail is always inserted

Fig. 22.4 An 18-year-old male with sequelae of hematogenous osteomyelitis of the *left humerus* before surgery (**a**). External fixator and sliding flexible intramedullary nailing (FIN); (**b**) X-ray taken after 21 days of lengthening; (**c**) X-ray taken at the end of the fixation period; (**d**) 1 year later, 80 mm lengthening of the arm was achieved and HI was 11.1 d/cm; (**e**) X-ray taken 1 year after removal of the external fixator. CT image of the upper end of the lengthened arm. Note extensive new bone formation in the medullary canal around the nail (**f**)

antegrade through the olecranon using a posterolateral approach.

One big advantage of combining the Ilizarov technique with FIN is that additional wires/pins can be inserted with the FIN construct in situ: anterior wire at the distal femur or proximal tibia, or middle-ring wires in bifocal lengthening. Thus, any external fixator wire/pin that might interfere with the intramedullary nails can be inserted after FIN is completed.

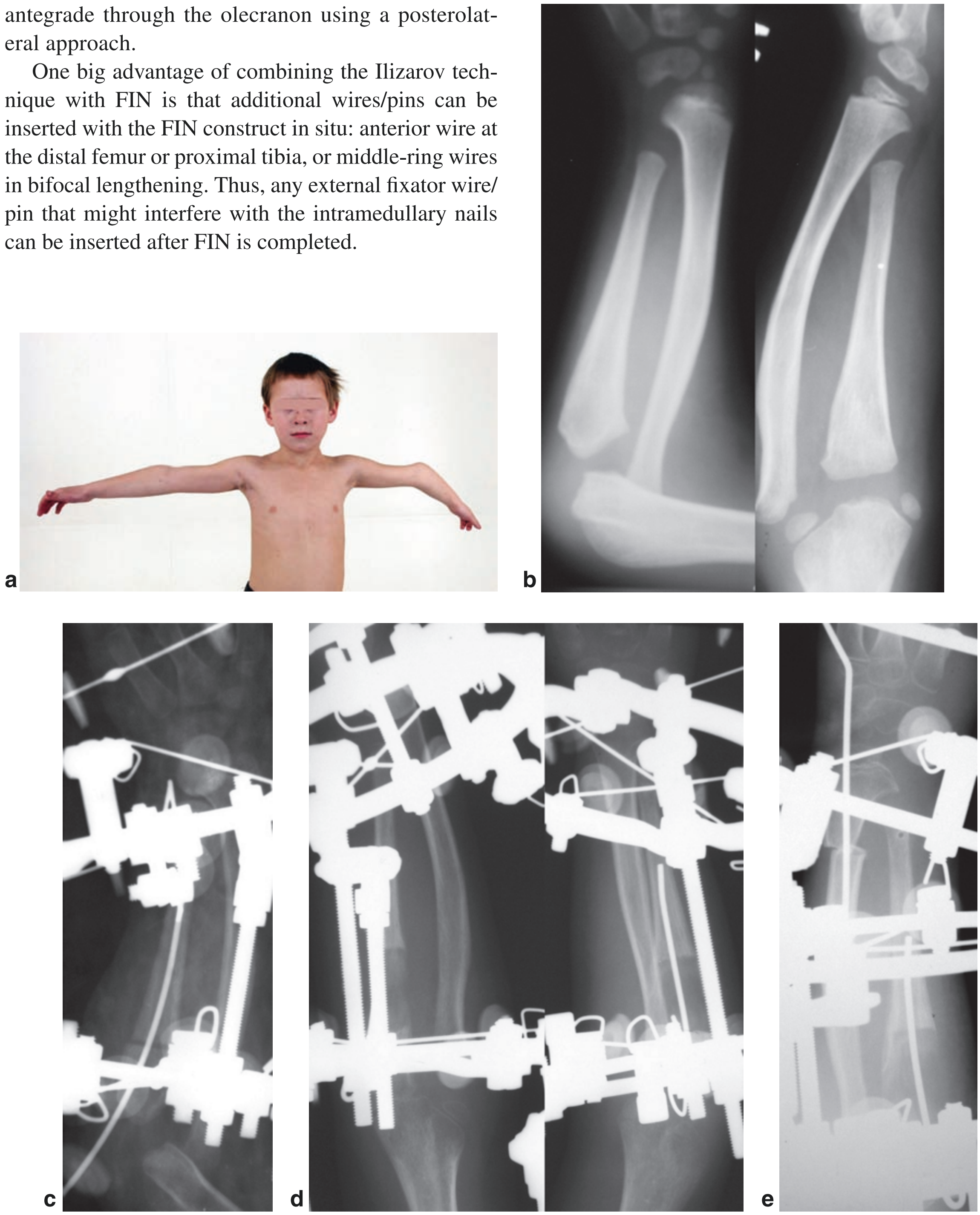

Fig. 22.5 A 6-year-old boy with congenital anomaly of the forearm (**a**); (**b**) preoperative X-ray of the forearm: short ulna, dislocation of the radial head; (**c**) external fixator, osteotomy, and FIN of the ulna using one single nail; (**d**) X-ray of the forearm after using distraction to lower the radial head; (**e**) osteotomy and FIN of the radius

f



g

Fig. 22.5 (*cont.*) (**f**) One month after removal of the external fixator; (**g**) AP X-ray taken 1 month after removal of the external fixator

Lengthening is usually initiated on the fourth to sixth postoperative day at a rate of 1 mm/day. As in any lengthening procedure, early weight bearing and joint mobilization are recommended to preserve function. Implant removal is a two-stage procedure. The external fixator can be removed as soon as the regenerate is radiographically healed. It is difficult to determine the time to healing with accuracy: the right time is when the regenerate zone is no longer detectable, and cortical continuity of at least three of the four cortices is seen on radiographs. Full weight bearing is allowed 6 weeks after removal of the Ilizarov fixator, and a plaster splint is routinely applied for a period of 2–4 weeks. It takes between 2 and 8 months after the end of the fixation period to restore normal range of motion (Figs. 22.1 and 22.3–22.5). Intramedullary nails can generally be removed between 2 and 6 months after removal of the external fixator.

22.3 Clinical Study

22.4 Materials and Methods

We have analyzed the outcomes of 68 lengthenings (79 bone segments, as 11 patients had multiple segment lengthening) in 65 patients (three patients underwent two operations) treated by the Ilizarov external fixator and FIN. Thirty-four patients were female and 31 were male. Mean age was 16.8 years (range, 4–43 years). In 40 cases (61.5%) ,the cause of the shortening was a congenital anomaly. Other etiologies included: infection in five cases (7.7%), trauma in six cases (9.2%), paralysis in four cases (6.2%), enchondromatosis or Ollier's disease in two cases (3.1%), and other causes in three (4.6%). Lengthening for short stature was performed in six patients (9.2%). Single-segment lengthening involved the humerus (5), forearm (11), femur (21), and tibia (20). Multiple-segment lengthenings included: five multiple-segment lengthenings of the lower limb, three bilateral tibial lengthenings, three crossed lengthenings of the lower limbs.

22.5 Results

Healing time was significantly reduced compared to lengthening with the Ilizarov technique alone. A comparison of healing times with combined Ilizarov/FIN vs. Ilizarov alone is presented in Table 22.1. From 2001 through 2004 (study period), both methods were used in the Orthopedic Department No 3, Russian Ilizarov Scientific Center for Restorative Traumatology and Orthopedics (Kurgan, Russia).

In our series, extensive, dense regenerate was consistently obtained. The changes observed on radiographs indicated rapid bone regeneration, which led us to increase the rate of distraction in some patients. In most cases, after 2 weeks of distraction, the interfragmentary gap was completely filled with a well-structured regenerate. The "growth zone" of the regenerate was 2–5 mm long and contained a large amount of bone trabeculae, and the periosteal region was expanded. Diameter of the regenerate was 2–6 mm larger than that of bone fragments. Once hardware was removed, CT images clearly showed abundant new bone formation along the intramedullary nail (Figs. 22.3i and 22.4f).

In five children, nail migration occurred between 30 days and 4 months after removal of the external fixator, when full weight bearing was resumed. This complication was observed 4 times in the femur and once in the tibia. In our whole series, there were no such complications as delayed union, vascular disorders, nonunion, or fracture of the regenerate after removal of the external fixator.

As a matter of fact, the healing index (HI) usually reported with the traditional Ilizarov method is 24–30 d/cm for the femur or the tibia, and 30–40 d/cm for the forearm [2, 3]. When automatic microdistraction mode is used, the external fixator is gradually lengthened at a rate of 1 mm/day (in 60 steps), and HI is brought down to 20–25 d/cm [4, 5]. When combined Ilizarov/FIN is used, HI can be reduced down to 14–22 d/cm for the lower limb and 20–25 d/ cm for the forerarm (Table 22.1).

The difference between cases treated with vs. without FIN was statistically significant ($p<0.05$) in the groups of patients with lower limb/upper limb length inequality due to congenital anomaly, infection, or trauma. The shortest fixation periods were observed in patients treated by automatic high-frequency lengthening.

22.6 Discussion

External fixators are still considered highly effective in treating LLD. However, according to publications [6–8], HI ranges from 38.6 to 45.0 d/cm for the femur, which means a long fixation period that may give rise to numerous complications. While acknowledging the clear-cut advantages of the Ilizarov method [2, 9, 10], one must also admit that the use of external fixators is fraught with complications such as pin-track infection, joint stiffness, discomfort [6, 11]. Rybka [12] noted an increased rate of pin-track infection and bleeding at the end of the fixation period.

There are several ways of accelerating the treatment process [4, 5]:

- Further optimize distraction conditions in order to increase the osteogenic capabilities of the tissues. Continuous lengthening for a whole nyctohemeral period provides faster, more homogeneous, and intensive formation of new bone;
- Shorten the duration of treatment by performing multifocal and/or multisegmental lengthening in cases in which significant correction is desired;
- Hasten healing by advancing the conditions for the transfer of compressive loads to the regenerate.

We have addressed the latter issue by combining two lengthening methods: Ilizarov method and FIN [5, 13], thus combining the proven benefits of FIN with the latest advances in lengthening device technology.

Our series of 68 limb lengthenings involving different bone segments demonstrates the manifest benefits of this combined method in terms of healing time. Average gain in external fixation time was approximately 2–9 days per centimeter of lengthening, depending on the bone segment involved. Reduction of the external fixation period resulted in faster restoration of adjacent joint motion. Therefore, the presence of intramedullary nails does not seem to

Table 22.1 Amount of lengthening and HI

Condition: lengthened segment/type of fixation		Ilizarov alone				Ilizarov + FIN			
		Number of cases	Mean age	Lengthen (cm)	Healing index (d/cm)	Number of cases	Mean age	Lengthen (cm)	Healing index (d/cm)
Congenital LLD	Femur (monofocal)	26	10.7 ± 0.68	5.0 ± 0.27	25.7 ± 1.17	8	13.9 ± 0.88	4.7 ± 0.73	19.5 ± 0.43
	Femur (bifocal)	13	11.5 ± 4.98	7.3 ± 1.51	20.0 ± 1.51	6	14.3 ± 1.86	7.0 ± 1.53	15.1 ± 2.38
	Tibia (monofocal)	30	12.5 ± 5.5	4.2 ± 0.34	31.4 ± 2.73	9	18.1 ± 3.9	3.7 ± 0.51	22.3 ± 1.59
	Tibia (bifocal)	17	9.6 ± 1.38	6.0 ± 0.5	21.9 ± 2.73	3	13.0 ± 2.0	9.9 ± 1.61	14.8 ± 2.5
	Multisegmental	10	13.4 ± 2.91	Femur: 3.9 ± 0.66 tibia: 3.0 ± 1.42	18.2 ± 1.29	3	15.0 ± 2.6	Femur: 5.7 ± 1.16 tibia: 4.3 ± 1.9	14.4 ± 5.6
Congenital ULD	Forearm	23	11.1 ± 1.07	4.0 ± 0.31	31.3 ± 2.04	9	13.2 ± 1.33	5.5 ± 0.44	23.8 ± 1.73
Sequelae of hematogenous osteomyelitis	Arm (bifocal)	12	12.6 ± 2.23	8.7 ± 2.03	15.6 ± 3.2	3	13.3 ± 1.2	9.0 ± 1.0	9.36 ± 1.74
Posttraumatic LLD	Femur (bifocal)	7	19.8 ± 2.11	7.9 ± 3.28	18.6 ± 3.54	4	15.4 ± 3.23	7.4 ± 0.47	12.9 ± 0.86
Sequelae of polyomyelitis	Tibia (monofocal)	3	13.5 ± 2.32	3.5 ± 1.09	29.1 ± 2.13	4	25.3 ± 4.08	3.2 ± 0.58	26.8 ± 1.75

LLD lower limb discrepancy; *ULD* upper limb discrepancy complicate or disturb rehabilitation after removal of the external fixator.

Furthermore, the contoured intramedullary nails do not interfere with endosteal tissue regeneration. On the contrary, the preserved intramedullary circulation stimulates tissue regeneration through redistribution of blood flow to periosteal structures [14, 15]. FIN improves stability at the diastasis by resisting translation (mostly) in the plane of the nails [14, 16]. It is a known fact that the more stable the lengthening site is, the faster it will heal [1, 17]. Launay [18] reported on a few forearm lengthenings using a unilateral external fixator in combination with one intramedullary guide wire (eight cases) or two guide wires (two cases). The aim of this method is to maintain correct axial alignment of the forearm during lengthening. According to Launay [18], there was a higher risk of delayed union when lengthening was performed without guide wire. He therefore recommends that the intramedullary wire be routinely used.

We are convinced that gradual sliding of the intramedullary nails through the regenerate during the lengthening process does stimulate new bone formation. Nail contouring plays an important role: to obtain this biological effect, the maximum of the curve should be located close to the osteotomy, opposite the entry hole. Thus, as nails slide, their apexes move slowly toward the regenerated bone area, which they reach at the end of the lengthening period.

Another notable advantage is that FIN does not prevent correction of bone deformities resulting from length inequality. On the contrary, it allows gradual correction of these deformities. Lastly, the external fixator can be removed and the intramedullary nails left in situ. They will initially serve as a supportive frame for the regenerate and then help stabilize this new bone.

However, it should be pointed out that combined Ilizarov/FIN requires expertise and familiarity with the FIN technique to create the prerequisite for distraction osteogenesis: preserve bone environment, periosteum, and particularly, the medullary vascularization, respect the biological rate of bone growth, maintain function by allowing early joint motion and weight bearing, and respect certain biomechanical rules. These conditions are, indeed, an essential part of the success of combined Ilizarov/FIN, but the key factor is the amount of experience of the surgeon with both bone lengthening techniques and FIN [14, 17].

22.7 Conclusion

FIN is a minimally aggressive internal fixation technique that was initially developed for treatment of long bone fractures in childhood. However, it has also proved to have several advantages when used in combination with external fixation. It is no surprise, since when performed according to the recommendations of the authors [14, 16, 17], FIN respects bone biology, which is essential in bone lengthening.

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23 Use of FIN for Correction of Deformities in Children with Familial Hypophosphatemic Rickets

Dimitri Popkov

23.1 Introduction

Flexible intramedullary nailing (FIN) is successfully used in bone lengthening, and assists in correcting associated bone deformities [1, 2].

Familial hypophosphatemic rickets (vitamin D-resistant) is responsible for the development of skeletal deformities. Corrective surgery is plagued by poor bone healing, and recurrent deformities resulting from renal phosphate-wasting disorders are frequent [3]. In these patients, we believe it is both logical and essential to restore the biomechanical axis in a single-stage procedure using staged osteotomy and fixation of bone fragments with the Ilizarov fixator [4].

This chapter describes the advantages of using a method, which combines the Ilizarov technique with FIN for the correction of bone deformities in children with familial hypophosphatemic rickets. Using intramedullary nails of various materials has allowed us to expand the treatment options.

23.2 Materials and Methods

This 3-year study (2002–2005) is quite limited since it involves only 11 children (five female and six male), whose age range from 4 to 17 years. In all children, the disease was discovered during the second year of life, as soon as they began to walk.

Most of the children had very severe genu varum, only two had genu valgum. Torsional malalignment, particularly internal tibial torsion, was found in all patients.

23.3 Surgical Technique

The main goal of surgical treatment is correction of femoral and tibial bone deformities through restoration of the biomechanical axis of the lower extremity. A realignment strategy is determined for each limb; both limbs are treated individually with an interval of 9 to 18 months between the two procedures.

The first surgical step is standard, consisting in application of the external fixator, followed by percutaneous osteotomies. Multisegmental fixation using the Ilizarov fixator is the mainstay of surgical treatment. Frame assembly (rings and half-rings) and position of olive wires are dictated by the anatomic location and severity of the deformities (Figs. 23.1–23.3).

The second step is FIN. If the deformity is located at only one level of the bone segment, one single osteotomy is planned. It is performed through two 10–20 mm longitudinal incisions centered over the metaphysis (Fig. 23.1). Two entry holes are created with an awl in an oblique direction toward the osteotomy, at some distance from the growth plate. It is recommended to select the metaphysis that is closest to the osteotomy in order to facilitate insertion of the intramedullary nails and proper orientation after intraoperative correction.

The 2–3 mm nails are contoured to achieve a curvature of about 40–50°. Tapered nail tips are bent to 30–40° over a length of 2–4 mm. Nails must be carefully advanced one at a time as far as the osteotomy site, following the natural bow of the diaphysis. Then, they are pushed across the site and directed to the opposite metaphysis. The maximum of the curve should be located at the osteotomy.

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DOI: 10.1007/978-3-642-03031-4_23, © Springer-Verlag Berlin Heidelberg 2010

Fig. 23.1 A 5-year-old girl with hypophosphatemic rickets before surgery. Clinical appearance (**a**, **b**). AP and lateral views, *right side* (**c**, **d**), *left side* (**e**, **f**). Ilizarov fixator in place for multisegmental fixation of the *right lower limb*: clinical appearance (**g**), X-rays (**h**)

Fig. 23.1 (*cont.*) Note the orientation of intramedullary nails to counter varus forces. View of the *right lower limb* 2 weeks after removal of the external fixator: biomechanical axis of the lower extremity was restored (**i**). Clinical appearance 1 year after removal of the external fixator (*right side*) and before surgery of the *left lower limb* (**j**, **k**). Surgical treatment of the *left lower limb*; AP and lateral X-rays: combined multisegmental external fixation/flexible intramedullary nailing (FIN). The biomechanical axis of the lower extremity was restored (**l**, **m**). View of the *left lower limb* 10 days after removal of the external fixator (**n**). Patient 1 year after removal of the external fixator (*left side*) (**o**). Length of fixation period for the *left side* was 48 days. View of the *right lower limb* 1 year after removal of the external fixator. Axial alignment still satisfactory (**p**, **q**)

After the nails have been inserted, the surgeon must reorient them so that their concavities are oriented toward the convexity of the deformity. This is quite difficult to achieve in a deformed bone. Once the nails are in place, frontal, sagittal, and torsional deformities are immediately corrected using the external fixator. Obviously, a proper FIN construct greatly facilitates realignment and prevents undesirable motion of bone fragments. Then, the nails can be recessed into the medullary canal.

It is also possible to associate the selected treatment method for bifocal correction of a complex deformity with FIN. In this case, bipolar combined FIN will be more appropriate. Each nail is contoured so that its concavity is oriented toward the convexity of the deformity close to the metaphysis into which it has been inserted (Fig. 23.2).

The free ends (trailing ends) of the nails must be cut relatively short and sharply bent (more than 90°) to prevent migration during realignment.

As in bone lengthening, additional wires/pins can be inserted through the ring holes with the FIN construct in place: mainly anterior metaphyseal wires, and some middle-ring wires in bifocal correction.

A slotted nail guide has been specially designed to facilitate advancement of the nail through the soft tissue layer, which may be thick in the metaphyseal area. It consists in a curved slotted metal guide, which holds and guides the nail both during insertion and advancement into the bone (Fig. 23.4). This instrument offers two major advantages. Firstly, it can be inserted through a mini incision, and is therefore particularly well suited to this treatment method since the nails are intended to remain in situ for several years, and will normally not need to be changed. Secondly, it has a unique design, which allows the use of contoured nails, and creates a smoothly curved path from the metaphyseal entry hole to the medullary canal.

The rationale for a slight overcorrection into valgus is prevention of neurologic complications (Fig. 23.3). Correction can be initiated as soon as the sixth to eighth postoperative day.

Once the external fixator has been removed, both regenerates are individually buttressed by at least one intramedullary nail, properly contoured and oriented so that it resists the natural tendency to develop secondary angular deformity in the regenerated bone area.

In our series, stainless steel nails have been used in five patients (first cases), and hydroxyapatite (HA)-coated titanium nails in six patients (subsequent cases).

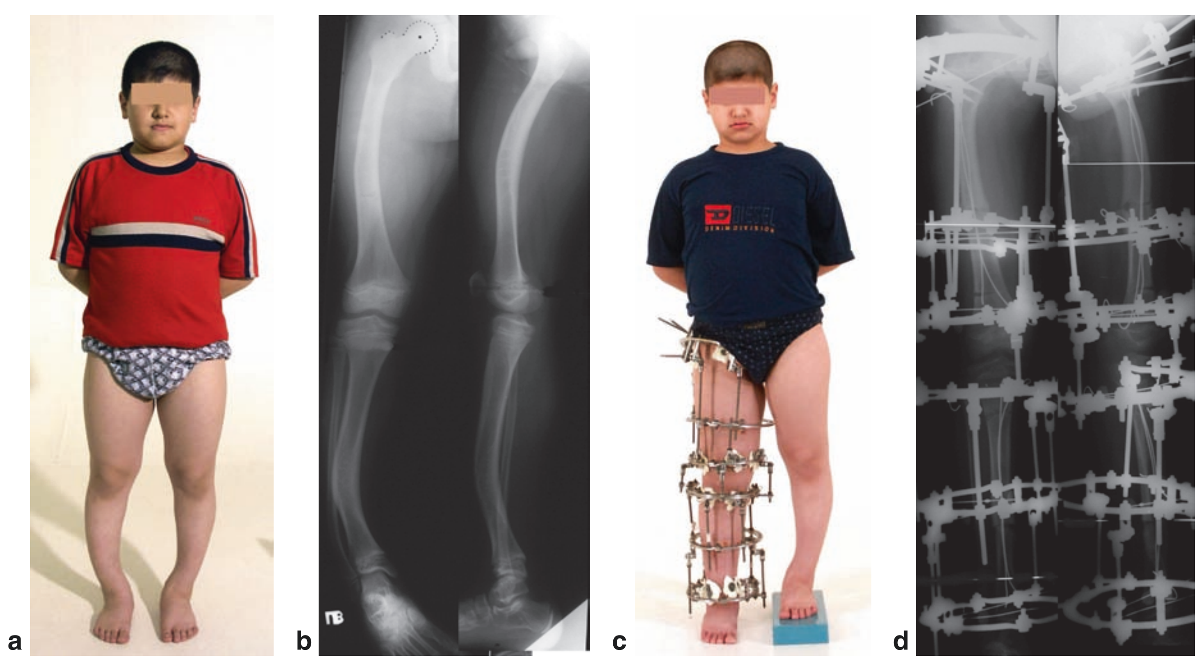


Fig. 23.2 A 10-year-old boy with familial hypophosphatemic rickets before surgery (**a**). AP and lateral X-rays of the *right lower limb* before surgical treatment (**b**). Ilizarov fixator in place for multisegmental fixation (**c**), AP and lateral X-rays of the *right lower extremity*. X-ray showing combined Ilizarov/FIN for multisegmental, multifocal fixation (**d**)

Fig. 23.2 (*cont.*) Sliding FIN (one retrograde nail, one antegrade nail) used both in the femur (**e**) and tibia (**f**). One year after removal of the external fixator (*right side*) and before surgery of the *left lower limb*. Length of fixation period was 81 days. Clinical appearance (**g**, **h**), AP and lateral X-rays (**i**, **j**)

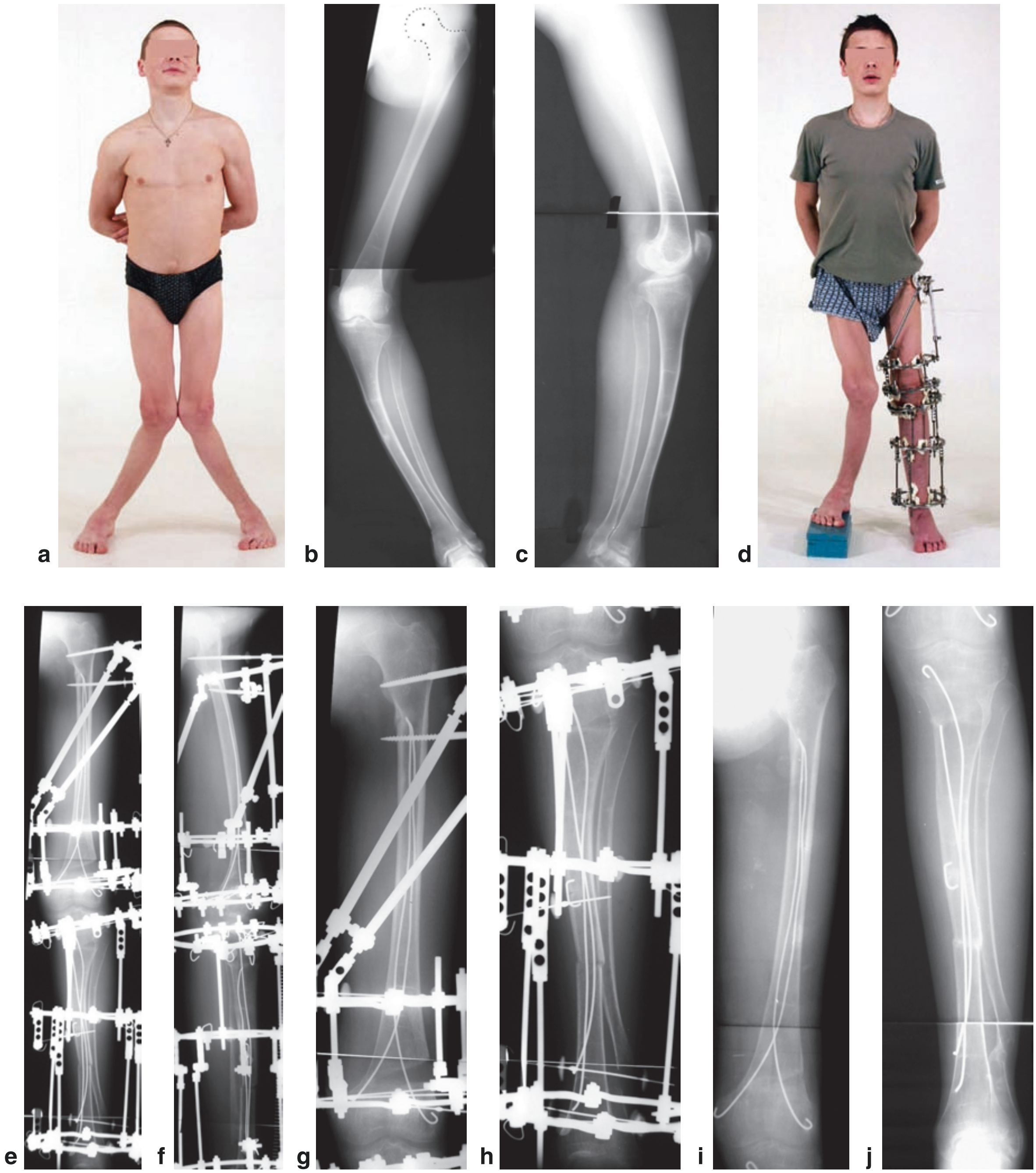
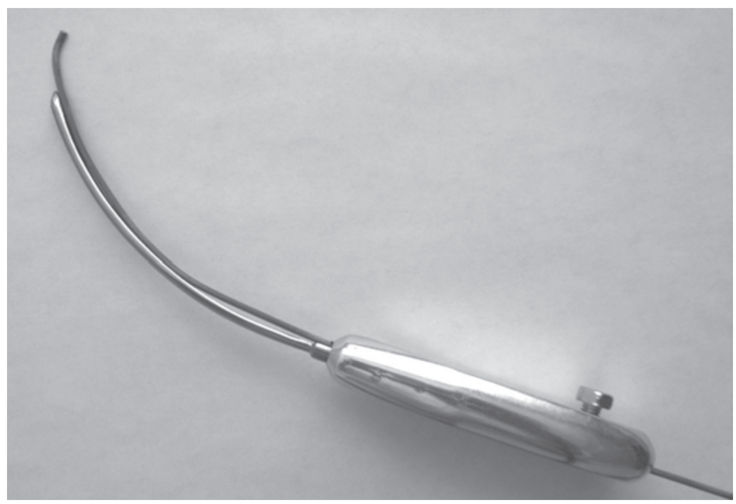


Fig. 23.3 A 25-year-old-male with familial hypophosphatemic ricket before surgery (**a**). AP and lateral X-rays of the *left lower limb* before surgical treatment (**b**, **c**). Ilizarov fixator in place for multisegmental, multifocal fixation (**d**). AP and lateral X-rays of the *left lower limb* showing combined Ilizarov/FIN for multisegmental, multifocal fixation. Biomechanical axis was restored (**e**, **f**). Correction of both femoral and tibial deformities was gradual. Note the orientation of intramedullary nails to counter valgus forces. Sliding FIN was used in the tibia due to double osteotomy (**g**, **h**). X-rays of the femur and tibia after removal of the external fixator (**i**, **j**)

Fig. 23.4 Intramedullary Nail Guide. The slot in the curved guide holds and guides the nail during insertion and advancement into the bone. The solid conical end of the guide facilitates passage through the metaphysis (**a**). Nail guide with a loaded nail (**b**)



23.4 Results

Length of the external fixation period with stainless steel nails vs. HA-coated titanium nails is presented in Table 23.1. A period of 136.8 ± 15.04 days has been used as a reference to compare with the results achieved with the traditional Ilizarov technique. Not only was the external fixation period significantly shorter when FIN was used, but there was no recurrence of the deformities as well. But of course, our mean 18-month follow-up is too short for a final evaluation of this method.

In two early cases, migration of too long intramedullary nails occurred within 2–4 months after removal of the external fixator, when full weight bearing was resumed. No nail-related complications have been experienced in the second group of patients. Actually, HA-coated nails act as permanent guides, which avoid the risk of skin impingement and eliminate the need for hardware removal.

23.5 Discussion

Preliminary results show that combined Ilizarov/ FIN may offer several advantages in the treatment of bone deformities in children with familial hypophosphatemic rickets (vitamin D-resistant), who obviously have abnormal healing. We think that in these patients, it would not be reasonable to use sliding FIN, which might interfere with remaining growth. The Ilizarov method allows full correction of all bone deformities by restoring the biomechanical axis of the lower limb. By buttressing the diaphysis, which is the common

Table 23.1 Length of external fixation period

Intramedullary nails	Number of patients	Mean age	External fixation period (in days)
Stainless steel	5	10.3 ± 3.2	112.7 ± 25.5
HA-coated titanium	6	6.5 ± 1.3	83.3 ± 10.8

location of the deformities and recurrent deformities typical of this disease [3], FIN provides a certain degree of stability and protects partly, if not completely, against secondary deformity, which may develop after removal of the external fixator. FIN has two key advantages:

- Owing to their elastic properties, the nails stimulate bone formation both during the external fixation period, thus reducing its length, and after removal of the Ilizarov fixator as they do not take all the axial mechanical loads, allowing bone mineralization to be maintained.
- Nails, which are properly contoured and oriented resist the natural tendency to bone angulation induced by muscles in the long run, after the external fixator has been removed. They provide a supportive frame to the bone and minimize the risk of gradual recurrence of secondary deformities.

Theoretically, as one of the main goals of surgical treatment is prevention of secondary bowing, combined Ilizarov/extensible nails might be an alternative, but this type of nail requires reshaping of the medullary canal with a reamer. Removing cortical bone results in thinning of cortices, which are already weak [5]. Furthermore, these nails can only be placed in a perfectly aligned canal, which means that full correction must be achieved intraoperatively; in some severe cases, it is just not feasible. Lastly, external fixator wires preclude proper insertion of the nail.

In contrast, the diameter of FIN nails can be changed intraoperatively without reaming the medullary canal [6–8]. Moreover, FIN provides the necessary intraoperative flexibility to meet the challenges of individual cases. FIN has a unique ability to actively resist the tendency to recurrence of the deformity after removal of the external fixator, provided that nails have been properly contoured and oriented [7]. Lastly, it is important to point out that FIN is perfectly harmless to the medullary artery [1, 2].

The hydroxyapatite coating of the nails promotes bone ingrowth for long-term biological fixation [9]. Histological studies of retrieved implants confirmed the osteoconductive properties of hydroxyapatite [10]. The bioactive hydroxyapatite coating serves a temporary osteoconductive role by preventing fibrous tissue interposition, thus reducing both healing time and length of the external fixation period, and preventing implant migration. We believe that the use of improved instrument system will open new possibilities for FIN.

23.6 Conclusion

Our series demonstrates that FIN yields good results in surgical correction of bone deformities in children with familial hypophosphatemic rickets (vitamin D-resistant):

- Shorter healing time in spite of poor bone development characteristic of this disease.
- Ability of a proper FIN construct to protect against the recurrence of secondary deformities.
- Hydroxyapatite coating of the intramedullary nails protects against late implant migration, and further reduces the length of the external fixation period.

Again, it must be emphasized that FIN is the only internal fixation method that provides the same optimal conditions for bone regeneration as the Ilizarov method. This is why combined Ilizarov/FIN yields such a remarkable outcome.

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24 FIN and Osteotomies

Tim Theologis, James Hui, and Pierre Lascombes

Generally speaking, flexible intramedullary nailing (FIN) is not particularly well suited for fixation of realignment or derotation osteotomies, as rigid stabilization is normally desirable to avoid losing all the benefits of the surgery, postoperatively. However, there have been several successful attempts. We describe here two specific indications for FIN.

24.1 Fixation of Femoral and Tibial Osteotomy in Diplegic Cerebral Palsy Children Using the FIN Technique

(Tim Theologis, Nicky Thompson, Andrew Wainwright)

Femoral and tibial derotation osteotomy are often part of single-stage multi-level (SSML) surgery in children with spastic diplegic cerebral palsy. The aim of the operation is to correct the rotational deformity of the above long bones, restore normal anatomy and improve gait. Authors have advocated proximal (intertrochanteric) or distal (diaphyseal or supracondylar) osteotomy for the femur, and there is ongoing debate about the advantages and disadvantages of each [1, 2].

Proximal and supracondylar osteotomies are usually fixed with the AO blade plate, while diaphyseal osteotomies are fixed using a straight plate. Rotational osteotomy of the tibia is usually performed at supramalleolar level to minimize the risk of nerve injury or compartment syndrome and is fixed with a straight plate. Furthermore, this allows early weight bearing with the protection of a below knee cast. Overall, results of rotational osteotomy as part of SSML are satisfactory. However, failure of the fixation following early weight bearing as well as nonunion, infection and incomplete correction are potential problems. Open techniques of osteotomy involve periosteal stripping, which may be responsible for some of the above complications. In addition, all these techniques using plate fixation require a significant amount of muscle dissection to gain adequate bone exposure, which may further compromise preexisting problems of weakness in these children. Muscle weakness is now a recognized problem in children with Cerebral Palsy. It is often masked by changes in muscle tone, predominantly spasticity, which may give the misleading impression of adequate strength. However, various therapeutic interventions that reduce spasticity, including dorsal rhizotomy and intrathecal Baclofen®, can unmask this underlying weakness. In 1999, Damiano [3] reported evidence of weakness following hamstrings lengthening in cerebral palsy. We have recently shown that strength changes following multilevel orthopedic surgery are greater, and persist longer than anticipated [4]. We quantified changes in muscle strength post multilevel surgery in children with cerebral palsy using dynamometry. We showed a mean reduction of lower limb strength of 17–58% at 6 months postoperatively, depending on the muscle group. We have also demonstrated that rehabilitation techniques following SSML surgery, focusing on strength training, significantly improved muscle strength, gait and motor function [5]. Despite this, the majority of lower limb muscle groups remained weaker than preoperatively at 1 year after surgery, although gait parameters remained significantly improved by the surgery.

We are therefore in the process of combining for the first time new "strength preserving" surgical techniques, allowing earlier mobilization, with resistance strength training at an earlier stage postoperatively, to provide a "strength preserving program", which should lead to faster and more optimal recovery for children with cerebral palsy following SSML surgery.

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DOI: 10.1007/978-3-642-03031-4_24, © Springer-Verlag Berlin Heidelberg 2010

As part of the "strength preserving program", we have changed our technique of performing and fixing rotational osteotomies of the femur and tibia. Our technique involves performing the osteotomy through a closed corticotomy to avoid muscle dissection and periosteal stripping. It also involves fixation with the FIN technique to achieve adequate stability of the osteotomy, which allows immediate postoperative weight bearing and early mobilization.

The use of the FIN fixation of fractures in children is well established. To our knowledge, this technique has not been previously used in elective rotational osteotomies. This is probably because of concerns on the rotational stability of the FIN fixation, particularly in older children. However, recent experimental work has shown adequate rotational stability of FIN fixation in the femur [6], which encouraged us to proceed with the introduction of this new technique.

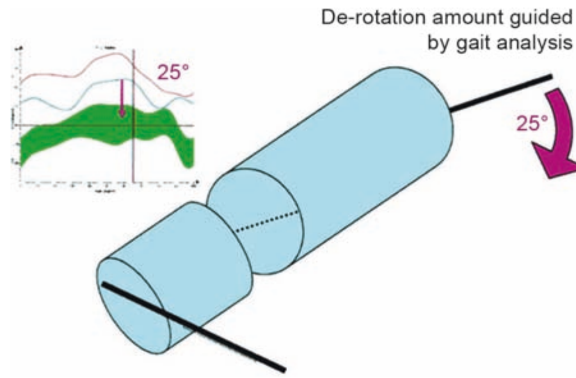

Fig. 24.1 The amount of rotational correction is determined based on the gait analysis findings. Here, there are 40° of internal rotation at the hip (normal value ranges from 10 to 15°). Therefore, a 25° external rotation femoral osteotomy is planned

24.1.1 Preoperative Assessment

The indications for rotational osteotomy of the femur or tibia, as part of SSML surgery, are based on clinical examination and gait analysis. The usual deformities requiring correction are femoral anteversion, expressed as increased internal rotation at the hip during walking, and external tibial torsion, causing external foot progression during walking or an external thigh-foot angle. We rarely obtain CT or MRI rotational studies as our aim is to correct the functional problem during gait. Therefore, we rely on the gait analysis findings to confirm the indications for treatment and to confirm adequate correction of the patient's rotational profile during walking postoperatively (Fig. 24.1).

24.1.2 Surgical Technique

Routine preparation and draping is used intraoperatively, and intravenous antibiotic prophylaxis is administered on induction of anesthesia.

24.1.2.1 Femoral Osteotomy

The nail diameter to be used is decided based on the diameter of the diaphysis on the preoperative radiographs (Chap. 5). The nails are prebent and inserted into the femur using the retrograde technique for both the medial and lateral sides. Both nails are advanced up to the isthmus of the diaphysis under fluoroscopy control. At this point, a K-wire is inserted centrally into the femoral neck, to be used as an anteversion angle reference and guide correction.

A corticotomy is then performed at the isthmus of the femoral diaphysis. The corticotomy technique includes multiple drill holes under fluoroscopy control. The osteotomy is then completed using a sharp and narrow osteotome. Alternatively, we have used the Gigli saw technique in some patients. Once the osteotomy is completed, the nails are carefully advanced proximally. No attempt to rotate the femur is made before the nails are a few centimeters within the proximal fragment, otherwise end to end apposition of the two ends of the osteotomy will be lost and advancement of the nails will be more difficult.

Once fluoroscopy confirms that both nails are a few centimeters within the proximal fragment, the osteotomy is rotated enough to achieve a normal anteversion angle of 10–15°. This is judged by the angle between the reference anteversion wire inserted in the femoral neck and the intracondylar knee axis. We have found that significant amount of rotational correction can be easily achieved with this closed method as the tension of the retracted muscles observed with the open method is not a problem. Following correction of the rotation, the nails are advanced proximally to their final position, then withdrawn 2 cm, cut distally and readvanced to their final position. Care is taken at this point not to distract the osteotomy site by vigorous hammering of the nails. Rotational stability is finally checked, the anteversion wire is removed and the wounds are closed with subcutaneous and subcuticular absorbable sutures.

24.1.2.2 Tibial Osteotomy

For the tibial derotation osteotomy, we use the same technique principles. Insertion of the nails is antegrade, and the osteotomy is performed in the mid- to lower diaphysis. The amount of rotation is easier to judge by comparing the relative position of the knee and the foot, and aligning the patellar tendon with the second toe. Any external immobilization is dictated by other simultaneous procedures. We do not use immobilization to protect the FIN fixation. However, soft tissue surgery around the knee may dictate the use of gaiters (knee immobilizers), and foot corrective surgery may require the use of below-knee walking casts.

24.1.3 Postoperative Care

Postoperative epidural anesthesia is used for postoperative pain control for 2–3 days. Physiotherapy commences on the first postoperative day and weight bearing on day 3 or 4.

Following SSML surgery, patients stay in hospital for 3 weeks to allow them to mobilize adequately and safely before returning to their home, where physiotherapy continues under the community services. Patients return to hospital 6 weeks postoperatively to undergo radiographs and confirm adequate healing of their osteotomies. Once this is the case, they commence the intensive muscle strengthening program, as inpatients for the first 1–2 weeks and as outpatients thereafter. They are followed up in Clinic, and if found to fall behind in their rehabilitation at any stage, further inpatient physiotherapy is offered.

24.1.4 Pilot Study

We obtained permission from our Hospital's Research and Development Committee to pilot this new technique in January 2005. We selected patients who were candidates for SSML and came to surgery at an age under 12 years. We are closely monitoring the patients who participate in this pilot study, and are comparing their progress with historical data from patients who have undergone conventional SSML in our hospital. The single most important and obvious advantage that FIN fixation offers is that it allows immediate weight bearing. Patients therefore avoid the nonweight bearing status for 4–6 weeks, which was necessary with conventional techniques. We believe that the overall complication rate, including infection, nonunion and failure of fixation will compare favorably to conventional techniques, although it is still early to draw any safe conclusions.

We have to date performed 16 femoral and four tibial derotation osteotomies in nine patients using FIN for fixation (Fig. 24.2). So far, adequate correction of the rotational abnormality as shown in the transverse plane kinematics of the hip, knee and foot was achieved in all patients and all osteotomies (Fig. 24.3). There have been no major complications and particularly no neurovascular injury, significant bleeding, infection, loss of fixation or nonunion. In one case, the osteotomy

Fig. 24.2 Radiographs taken after derotation osteotomies: femur (**a**) and tibia (**b**)

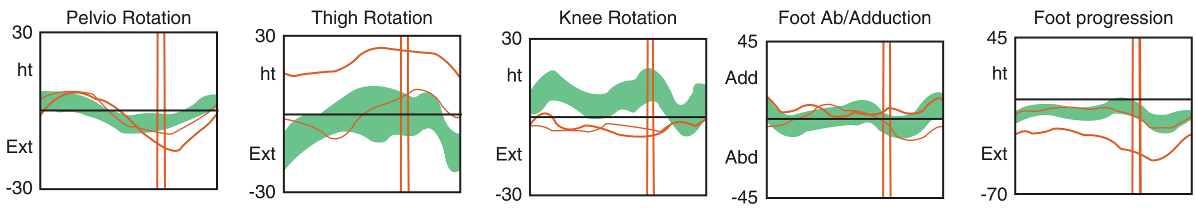

Fig. 24.3 Study of transverse plane kinematics of the lower extremity – the *thick orange line* represents the *left lower limb*, preoperatively, and the *thin orange line* the *left lower limb*, postoperatively after the femoral and tibial osteotomies. Note the significant amount of preoperative internal rotation at the hip, and the external thigh-foot angle resulting from external tibial torsion. The amount of correction is determined based on these graphs. Postoperative curves show adequate correction of the patient's rotational profile

propagated medially in an oblique direction. Despite that, adequate rotational correction and subsequent healing were achieved. In another case, the medial femoral nail was advanced excessively to a position abutting the proximal femoral physis. To date, no evidence of growth disturbance is evident on the radiographs.

24.2 Conclusion

In conclusion, our pilot study indicates that our technique of using closed corticotomy and FIN fixation for rotational osteotomy of the femur and tibia as part of SSML surgery may be carrying significant advantages over conventional techniques. We will continue with more patients and longer follow-up to establish the advantages of our "strength preserving program" in children with diplegic cerebral palsy.

24.3 Posttraumatic Malunion of Forearm Fractures

(James Hui, Pierre Lascombes)

It is widely recognized that malunion resulting from insufficient reduction of fractures of both bones of the forearm remodels poorly with growth (correction is approximately 1° per year) and causes severe restriction of pronation-supination (Chap. 16).

Surgical correction is proposed to patients with unacceptable angular deformity of one or both bones of the forearm. The routine protocol is as follows: incision is made over the apex of the deformity; closed wedge osteotomy is performed (same angle as that of the deformity); FIN nails are inserted using the same technique as in forearm fractures: retrograde radial nail insertion and/or antegrade ulnar nail insertion. The nails are pushed across the osteotomy site under direct visual control (Fig. 24.4). At the end of the procedure, the nails are rotated so that their concavities are oriented toward the convexity of the initial deformity. The surgeon takes advantage of the general anesthesia to slowly move the forearm alternately into maximum pronation and supination in order to gain as much range of motion as possible before the child wakes up from anesthesia.

Postoperative management varies according to authors. For the Nancy school surgeons, it is important to mobilize the operated limb as early as possible. Therefore, rehabilitation, both passive and active, is started immediately using a CPM machine and analgesic medication, through the largest possible range of pronation and supination. In contrast, in Singapore, 2 weeks immobilization followed by aggressive rehabilitation is the rule.

When we did our first case (Fig. 24.5), we informed the adolescent and his parents of the potential risk of nonunion of at least one of the two bones. The radius healed rapidly, in less than 3 months. The ulna eventually united by about 6 months. The gain in range of motion was really impressive.

Some of our subsequent cases involved only the radius. Results were consistently good, with full correction of malunion in all three planes and significant improvement of range of motion (Fig. 24.6).

One of the main advantages of FIN over screw plates is that it allows correction of rotational malalignment (if any) at the end of the procedure through forced pronation, followed by forced supination: cracking sounds are heard during realignment. Early rehabilitation is the key to preservation of the range of motion achieved intraoperatively. One of the drawbacks is the potential risk of nonunion, which requires revision surgery.

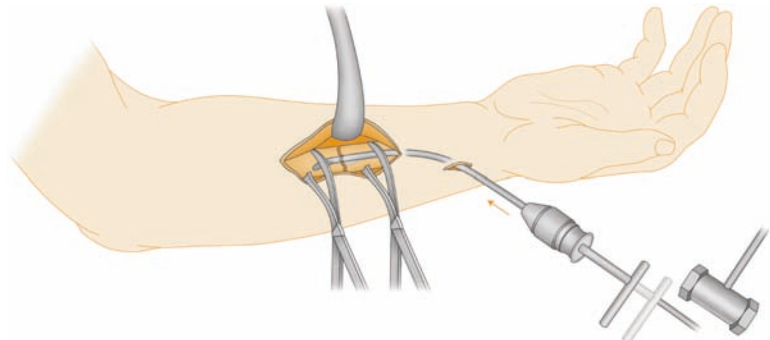

Fig. 24.4 Insertion of the radial nail after osteotomy

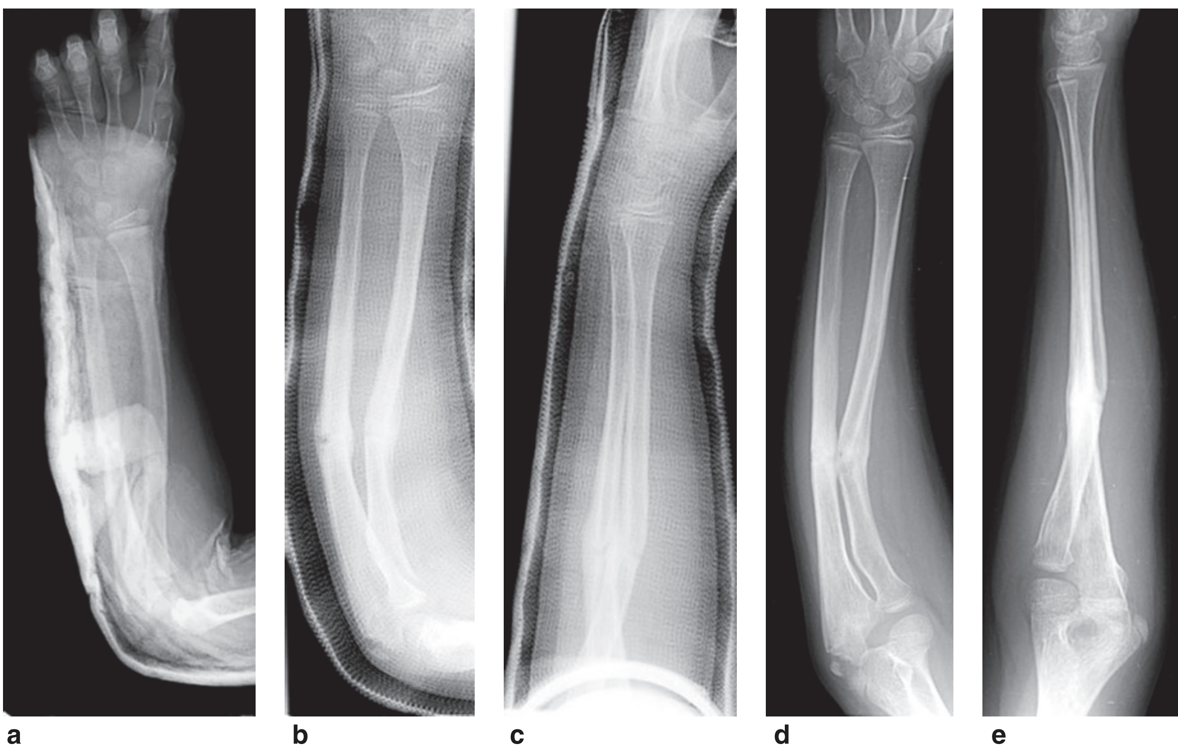

Fig. 24.5 An 8-year-old boy with fracture of both bones of the forearm treated nonoperatively (**a**). Three years later (at 11 years), the boy sustained a new fracture which was treated with flexible intramedullary nailing (FIN). But the nails were removed prematurely and 6 month later, a third fracture occurred which was treated again nonoperatively (**b**, **c**). Malunion resulted, which caused severe restriction of pronation and supination (**d**, **e**)

Fig. 24.5 (*cont.*). He underwent a double osteotomy of the radius and ulna which was fixed with FIN (**f**). Cast immobilization for 2 weeks (**g**). The 2-year outcome was very satisfactory both clinically (**h**, **i**) and radiologically (**j**, **k**)

Fig. 24.6 A 12-year-old girl with radial malunion in 30° of flexion secondary to an unreduced fracture. The total range of pronation/ supination did not exceed 20° (**a**). CT scan showed the close contact between radius and ulna that was responsible for limited rotation of the radius around the ulna (**b**). Extension closed wedge osteotomy of the radius was fixed by retrograde FIN using one 2.5 mm stainless steel nail with concavity facing anteriorly (**c**). At the end of the procedure, 70° of pronation and 80° of supination were eventually achieved through alternate rotational movements. Postoperative rehabilitation was started immediately. At 5 weeks, healing was well under way (**d**, **e**). The nails were removed at 1 year: both bones of the forearm were correctly aligned and the total range of pronation/supination was 150° (**f**, **g**) [courtesy of P. Lascombes]

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25 Conclusion

Pierre Lascombes

The Nancy University Hospital Department of Pediatric Orthopedics was first headed by Prof. J. Prévot whom I succeeded in 1994. So far, over 1,700 children and adolescents have been treated in our department for one or several fractures by flexible intramedullary nailing (FIN) [1].

FIN was initially used for treatment of femoral shaft fractures. In the 1980s, between 20 and 30 FINs per year were performed. This number has decreased during the past years due to the changing trend in the nature of road traffic accidents. Today, we treat more and more adolescents with ipsilateral fractures of the femur and tibia sustained during scooter accidents, which are aggravated by neurovascular injuries.

FIN of the femur is a reliable fixation method, provided that its essential mechanical principles are respected. It is even more important in heavy and/or older children. Distal positioning and nail trimming is critical.

Fracture of both bones of the forearm is the second most common occurrence. How wonderful it is to see these children, 2 months after their injury, with near normal forearm function and inconspicuous scars! Such a good outcome is attributable to the quality of the reduction provided by FIN: once the intramedullary nails have crossed the fracture site, anatomic reduction is warranted. Many patients have benefited from this advanced technique, which combines one radial nail and one ulnar nail with opposing curves.

In less common injuries like diaphyseal fractures of the humerus and tibia, FIN proves to be a good option in those cases where any other treatment and particularly nonoperative treatment would be inappropriate or unreasonable. Excellent results have been achieved in both the humerus and the tibia, although tibial FIN is technically more demanding. As a matter of fact, the triangular geometry of the proximal tibia makes it more difficult to respect the basic principle of the "two nails with opposing curves," and the use of a third fibular nail or cast boot immobilization for 3 weeks may be necessary. We have had a few nonunions, all of which involved the tibia and occurred in older adolescents.

In metaphyseal fractures, FIN of the neck of the humerus is just an adaptation of the Hackethal technique to suit children and adolescents [2]. The main technical difficulty lies in the initial reduction performed on the operating table; subsequent nailing is a straightforward procedure.

It is in supracondylar fractures of the humerus that FIN yields the most outstanding results: the Stateof-the-Art of the Nancy method. These fractures may seem difficult to manage to a surgeon who is not familiar with the method. Actually, it is a matter of experience and skillfulness: both nails are easily brought down to the fracture site, and then pushed across the fracture site with the help of a slotted hammer after the lower end of the humerus has been reduced. Achieving anatomic reduction is a require320 ment, which explains our very low rate of cubitus varus and/or valgus deformity.

Treatment of radial neck fractures using one single intramedullary nail is a tour de force, the stroke of genius of Dr. Jean-Paul Métaizeau. Except in irreducible fractures, FIN results are so amazing that arthrotomy has become a contraindication.

Lastly, many years ago, hand surgeons gave up crossed wires and started to use intramedullary wires for fixation of metacarpal and phalangeal fractures. Crossed wire constructs were often unstable and not really suited for early mobilization.

FIN has a number of advantages. The rate of unexpected revisions is much lower than that reported in series of conservatively treated patients. FIN eliminates the need for cast immobilization in almost all fractures, with the exception of radial neck fractures in

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DOI: 10.1007/978-3-642-03031-4_25, © Springer-Verlag Berlin Heidelberg 2010

young children and 50% of tibial fractures. For all other fractures, no immobilization is necessary, which allows early functional recovery. Contrary to what is observed in series of intramedullary nails implanted prior to closure of the physis of the greater trochanter, we have had no case of FIN-related necrosis of the femoral head, which is one of the most common postoperative complications associated with treatment of femoral fractures [3]. Also, contrary to findings in some publications about external fixation, we have only had one refracture due to a new high-energy trauma [4, 5]. As regards forearm, contrary to what is seen after removal of screw plates, we have not experienced any recurrent fracture since we have got into the habit of leaving the nails in situ for 6 months, or any other type of late fracture [6].

However, not all complications and adverse effects can be avoided, and both the patients and their families must be made aware of this. The most serious complication remains diaphyseal osteomyelitis, with an incidence of 0.2%.

All this makes us very proud of our achievements: Developing the innovative concepts of our elders, namely Jean-Paul Métaizeau and Jean-Noël Ligier; supervising several generations of chief residents and residents; training surgeons worldwide so as to provide high-quality trauma care to injured children and adolescents. But the outcome of an FIN procedure relies essentially on experience and skillfulness of the operating surgeon. Therefore, both training of newly qualified surgeons and continuing education are indispensable to ensure strict adherence to the basic principles of FIN, which are critical to the success of this method, particularly in adolescents.

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Appendix

Patient Information

Your child has a fracture and will be surgically treated under general anesthesia. The procedure consists in reduction of the fracture, which may necessitate an open approach, and internal fixation using flexible intramedullary nailing (FIN). Of all currently used fixation methods (screw plates, intramedullary nails, external fixators), FIN is best suited for children and adolescents, because it does not interfere with the growth process and has the lowest complication rate.

Still, potential complications may occur:

- Complications related to general anesthesia
- Complications related to fracture and healing process:
  - Pain, swelling, hematoma
  - Skin lesions
  - Vascular lesions, compartment syndrome, ischemia
  - Sensory deficit (sensory loss, paresthesia, etc.) and/ or motor deficit (paralysis, paresis)
  - Postoperative complications related to prolonged bed rest, including phlebitis and deep venous thrombosis (DVT)
  - Joint stiffness, amyotrophia, algodystrophy
  - Delayed union, nonunion
  - Growth-related complications, including angular deformity and/or leg length discrepancy
  - Refracture, recurrent fracture
  - Malunion or bone deformity
  - Degenerative arthritis
- Complications related to implantation of a medical device:
  - Wound hematoma.
  - Superficial and/or deep infection.
  - Vascular and/or neurologic complications.
  - Incomplete reduction or secondary displacement requiring surgical revision.
  - Implant breakage.
  - Hypertrophic scars.
  - Complications related to hardware removal (implants intended for temporary fixation).
- FIN-related complications:
  - Nail ends are left proud of the bone surface to facilitate later removal; prominent nails may break through the skin or result in painful joint motion. Prominence disappears as soon as nails are removed. In the meantime, the child must avoid excessive range of motion, and is requested to gently mobilize the skin area around the cut ends of the nails to prevent tissue adhesion.

If your child experiences unusual pain or discomfort during the postoperative period, immediately consult your medical doctor or the surgeon.

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DOI: 10.1007/978-3-642-03031-4_Appendix, © Springer-Verlag Berlin Heidelberg 2010

Subject Index