Forearm Fractures

48

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Contents

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Abstract

Diaphyseal fractures of the ulna and radius are frequent injuries in the pediatric population. These fractures are typically the result of low-energy falls onto an outstretched hand. Nevertheless, a careful assessment of the patient is imperative, with evaluation of the skin and soft tissues for lacerations, compartment swelling, as well as a complete neurovascular examination. The majority of forearm fractures are closed injuries without associated nerve injuries or vascular compromise. These fractures are most often best treated with primary closed reduction and cast immobilization.

Forearm fractures that necessitate surgical fixation include irreducible or unstable fractures that have failed an attempt at closed reduction, open fractures, and fractures associated with severe soft tissue trauma, "floating elbow" injuries, vascular injury, or compartment syndrome. Flexible intramedullary nail fixation is the treatment of choice for most children and skeletally immature adolescents. Surgical treatment is generally associated with an increased number of complications, especially in children older than 10 years of age. Compartment syndrome, infections, nerve injuries, and extensor tendon injuries are the most common complications associated with surgical treatment. This chapter will focus on closed reduction and casting, surgical treatments, and avoidance of complications.

Part A: Nonoperative Treatment

Introduction

Forearm fractures in children and adolescents are one of the most common causes for children to receive orthopedic care (Chung and Spilson 2001). The majority of these fractures are best treated with closed reduction and cast immobilization (Jones and Weiner 1999). In the past 10–15 years, however, an increasing number of children with these injuries are undergoing surgical treatment, especially flexible intramedullary nail fixation (Cheng et al. 1999; Flynn et al. 2010). The indications for this procedure and the best methods of fixation are evolving. Many children, particularly those older than 10–12 years of age, with unstable fractures of the forearm may be best treated with surgery. However, complications related to surgical treatment are not uncommon and must be taken into consideration when deciding between operative and nonoperative management. Despite extensive experience with nail fixation, complications such as extensor tendon injuries, nerve injuries, and prolonged fracture healing remain problems to overcome.

Epidemiology

Approximately 1/100 children per year will experience a forearm fracture, with most occurring in the distal radius (Chung and Spilson 2001). The age of fracture incidence peaks in boys and girls at age 9, but boys also have a second peak at the age of 14 (Landin 1983). Forearm fractures occur with equal frequency in males and females until the age of 11 or 12; after that, males sustain these fractures almost twice as frequently as females. In addition to being a common location for primary injury, the pediatric forearm is the most common site of *refracture* after healing of a fracture in the same location (Landin 1997).

Mechanism of Injury

The majority of forearm fractures result from a fall onto an outstretched hand (Aktas et al. 1999). These injuries typically occur from low- and moderate-energy mechanisms such as falls from a step or playground equipment or during sports activities. Direct blows to the forearm represent another important mechanism. Forearm fractures are the type of fracture most commonly associated with trampoline injuries and the second most common fracture seen after falls from monkey bars (Waltzman et al. 1999). In one report from Finland, the incidence of forearm fractures has been increasing, with the rising use of trampolines by children being cited as a potential reason for the change (Sinikumpu et al. 2012). High-energy mechanisms, such as being struck by a motor vehicle or falling off a motorized vehicle, are less common but are associated with an increased risk of concomitant serious injuries, as well as the potential for severe soft tissue damage and neurovascular injury to extremities.

Applied Anatomy

The radius and ulna are the two bones that make up the forearm, with the radius being the more lateral bone. The shaft of the radius has three sides, two of which are convex. One convexity is along the midportion of the bone and is 10° with the apex lateral-radial. The other convexity is 15° with its apex medial and more proximal (Firl and Wunsch 2004). The radial bow refers to the midportion deviation of the radius. Forearm rotation is dependent on normal anatomic contour of the radial bow (Sage 1959). Two important bony landmarks of the radius are the radial styloid and the bicipital tuberosity. The radial styloid is a lateral, distal prominence, and the bicipital tuberosity is an anteromedial prominence. These two structures are oriented slightly less than 180° from each other (Milch 1944). Nine muscles attach to the radius: the abductor pollicis longus, biceps, brachioradialis, extensor pollicis brevis, flexor digitorum superficialis, flexor pollicis longus, pronator quadratus, pronator teres, and supinator (Doyle 2003). The distal epiphysis of the radius appears near the age of 1 year, while the proximal epiphysis emerges around 4 to 6 years old. (Silberstein et al. 1982, Ogden et al. 1981). Approximately 70-80 % of longitudinal growth of the radius occurs at the distal epiphysis (Ogden et al. 1981). Physeal closure of the radius is variable and gender dependent; the proximal physis closes first near 14–15 years of age, followed by the distal physis at around 15–18 years old (Kraus et al. 2011, Ogden 1982).

The ulna is prism shaped proximally and becomes more cylindrical distally (Milch 1944). The distal styloid process and proximal coronoid process are important landmarks of the ulna. The syloid is dorsal and the coronoid is volar, oriented almost 180° from each other (Milch 1944). Fourteen muscles attach to the ulna: abductor pollicis longus, anconeus, biceps, brachialis, extensor carpi ulnaris, extensor indicis proprius, extensor pollicis longus, flexor carpi ulnaris, flexor digitorum profundus, flexor digitorum superficialis, pronator teres, pronator quadratus, supinator, and triceps (Doyle 2003). The epiphysis of the distal ulna appears in conjunction with the radius at about 4 to 6 years old. The proximal olecranon apophysis ossifies near 9 to 10 years old (Silberstein et al. 1982 - [the one about the ulna]). Similar to the radius, 70-80 % of longitudinal growth of the ulna occurs at the distal epiphysis (Ogden et al. 1981). Physeal closure of the ulna occurs in the same stages as the radius (Ogden 1982).

The forearm contains major vessels and nerves in continuation from the proximal upper extremity. The vascular composition of the forearm is supplied by contributions from the radial and ulnar arteries. The radial artery lies superficial to the pronator teres on the flexor digitorum superficialis and flexor pollicis longus, lateral to the flexor carpi radialis (Standring et al. 2008). It gives off branches to the radial recurrent artery and several muscular branches. The ulnar artery is deep to the radial head of the pronator teres, on the flexor digitorum profundus, and lateral to the ulnar nerve. It gives rise to the anterior ulnar recurrent artery, posterior ulnar recurrent artery, common interosseous artery, and muscular branches. Important nerves include the radial, ulnar, and median nerves, as well as the anterior and posterior interosseous nerves, and the lateral and medial cutaneous nerves of the forearm (Standring et al. 2008).

The radius and ulna comprise a ring of bone in the forearm that is reinforced proximally by the articulations with the distal humerus and the ligamentous connections of the proximal radioulnar joint and distally through the articulations with the carpus and the distal radioulnar joint complex. The interosseous membrane runs obliquely between the radius and ulna providing stability to the ring but permitting rotation of the radius around the ulna. The normal forearm rotates through an arc of 160°, with approximately 80° of pronation and 80° of supination. It is important to understand that forearm rotation is best measured at the level of the distal radius and ulna, not by assessing the position of the hand. As much as 40° of rotation may occur through the radiocarpal joint, making forearm rotational measurements less precise. This carpal motion, however, may improve the function of some patients by compensating for loss of forearm rotation that resulted from an injury or congenital difference.

Pathoanatomy

When falling onto an outstretched hand, the most common mechanism of both-bone forearm fractures, loading force is transmitted to the radius, which typically fails first, followed by failure of the ulna if the force magnitude is great enough (Treadwell et al. 1984). The rotational position of the forearm upon impact (McGinley et al. 2003) and the amount of energy applied dictate the fracture locations. If the forearm is loaded while in supination, the radial fracture occurs proximal to the ulna fracture while the reverse is true if the forearm is pronated on impact. The fractures occur at the same level if the forearm is neutrally rotated when the hand strikes the ground. Additionally, a large direct force, such as being struck with a baseball bat, may cause fractures that occur at the same level. Approximately 75 % of fractures occur in the distal third of the forearm, 15 % in the middle third, and 5 % in the proximal third (Thomas et al. 1975).

Single-bone forearm fractures, i.e., isolated fractures of either the radius or ulnar shaft, may occur as well. These are most commonly the result of a direct blow to either bone or lower-energy mechanisms in younger children. An isolated fracture of the ulnar shaft, however, must raise suspicion for an ipsilateral subluxation or dislocation of the radial head (Monteggia fracture). Similarly, an isolated fracture of the radial shaft demands careful assessment of the distal radioulnar joint for dislocation of the distal ulna (Galeazzi fracture) or a displaced fracture through the ulnar physis (Galeazzi equivalent).

Assessment

Signs and Symptoms

A child with a forearm fracture typically presents after a traumatic injury complaining of pain, swelling, and, if the fracture is displaced, a visible deformity of the involved extremity. Occasionally, pain with bearing weight on the involved extremity and painful range of motion, particularly pronation and supination (Soong and Rocke 1990), are the chief complaints, especially with nondisplaced fractures or incomplete fractures with minimal swelling. While most forearm fractures present as isolated injuries, it is critical that a careful history is taken and a primary physical assessment including vital signs and the cardiovascular parameters is performed for patients who sustain these injuries from higher-energy mechanisms, such as a fall from a sizable height or a motor vehicle accident. This will allow identification of other potentially more serious injuries of the head, thorax, and abdomen.

Once a fracture is suspected, the extremity is inspected for areas of swelling, open wounds with exposed bone, and other soft tissue findings such as bleeding, abrasions, and tissue loss. The radius and ulna are palpated along their lengths, and the ipsilateral elbow and wrist joints are assessed for swelling, tenderness, and painful or limited range of motion. The soft tissue compartments are palpated to identify extreme tautness, which may indicate an impending compartment syndrome. Painful passive stretch of the fingers is also suggestive of an impending compartment syndrome but may also be seen in those with severe pain from the fractures, as is common in fractures with displacement.

A complete neurovascular exam includes motor and sensory testing of the ulnar, radial, and median nerves. This may be done easily with cooperative patients who are older than 5–6 years of age in a systematic way similar to adults. However, it may be difficult to adequately assess younger children, individuals with intellectual impairments, and patients who are experiencing severe anxiety or pain. Observing these types of patients or engaging them in simple tasks, such as grabbing a pen, may provide clues to nerve function. Another method suggested by some is to play the familiar child's game of "rock-paper-scissors" with the patient, a technique that may permit active assessment of the radial, ulnar, and median nerve motor function (Davidson 2003).

Imaging

High-quality anteroposterior (AP) and lateral radiographs of the entire forearm, including the elbow and wrist, are necessary to evaluate potential forearm fractures effectively. If the child is able to tolerate gentle positioning based on his or her degree of discomfort, these radiographs are ideally taken with the elbow and wrist extended and the forearm neutrally rotated. Grossly unstable forearm fractures should be protected in a long-arm splint prior to transport to the radiology suite, for the child's comfort and to reduce the risk of further soft tissue and neurovascular injury. Advanced imaging of forearm fractures is indicated in rare cases. Computed tomography (CT) may be useful to assess intra-articular extension of fracture lines and for assessing the extent of bone cysts or other bony defects when a pathologic fracture is suspected. Magnetic resonance imaging (MRI), however, is the best advanced imaging modality for assessing potential pathologic fractures that may have occurred secondary to tumors or infectious processes.

Associated Injuries

Most forearm fractures are isolated injuries resulting from low- and intermediate-energy traumatic events. In these patients, the most important associated findings *not to miss* include open fractures, nerve or vascular injuries, and impending compartment syndromes in the affected extremity. Additionally, careful clinical evaluation of the entire extremity and thorough scrutiny of the forearm radiographs, including the elbow and wrist in all cases, will prevent the surgeon from missing Monteggia fracture dislocations, Galeazzi fractures, and their equivalents unique to pediatric patients (Letts et al. 1985; Landfried et al. 1991). A simultaneous ipsilateral fracture of the forearm and a supracondylar fracture of the humerus has been reported with a prevalence of 5.3 %. Typically these are a result of high-energy mechanisms and are associated with nerve injuries and/or open fractures (Roposch et al. 2001).

For those patients who present with forearm fractures from high-energy mechanisms, such as falls from a significant height or motor vehicle trauma, emergency department evaluation must consider the possibility of more serious associated injuries. Establishing the ABCs first is paramount for these patients. Head trauma, thoracoabdominal injuries, spine fractures, and other life-threatening conditions must first be ruled out before the fractured extremity is fully assessed. Provisional realignment and splinting of an obviously injured forearm provides pain relief and protects the extremity while resuscitation and further evaluation are completed. A secondary orthopedic survey may then be performed, with particular attention paid to the entire injured extremity to identify ipsilateral fractures of the shoulder, humerus, elbow, wrist, and hand.

Classification

No specific classification exists for pediatric forearm fractures. Forearm fractures are typically described based on which bones are fractured (both bones or single bone), the level of the fracture within the forearm (distal, middle, or proximal third), and the fracture pattern of each bone (plastic deformation, greenstick, complete). Fracture alignment is determined by measuring the degrees of angulation in the anteroposterior (AP) and lateral planes, the amount of translation of the fracture fragments relative to each other, and the rotational alignment of the fracture fragments.

Fracture Patterns

Plastic Deformation

Plastic deformation, when the bone is "bent but not broken," occurs when the load placed on

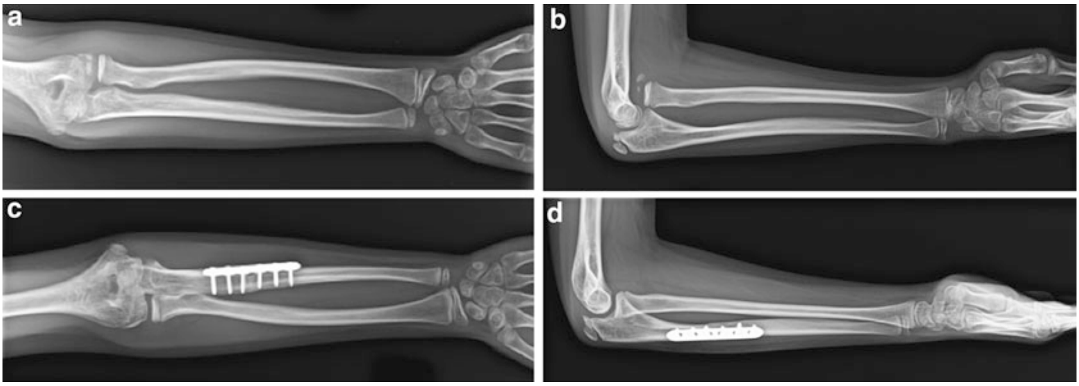

Fig. 1 A nine-year-old female sustained a Monteggia fracture dislocation (plastic deformation of the ulna and radial head dislocation, AP-**a** and lateral-**b**). Reduction of the radial head was achieved by correction of the ulnar bowing using an osteotomy and plate fixation (AP-**c** and lateral-**d**)

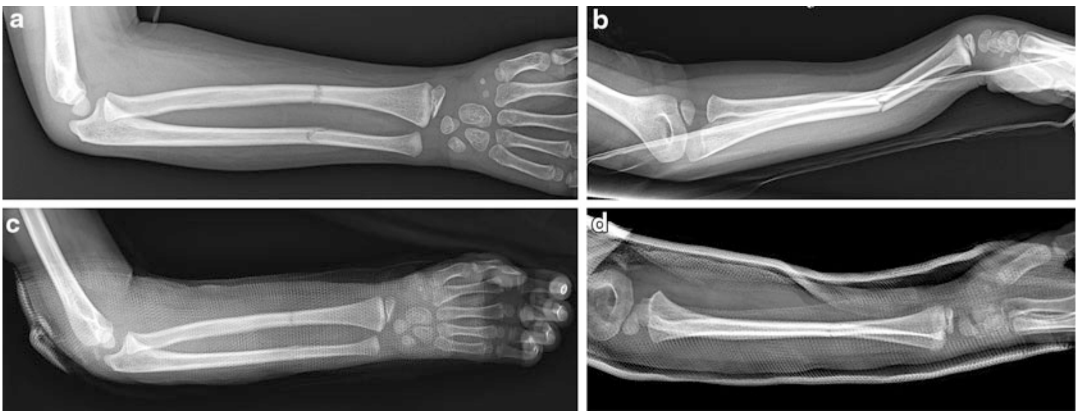

Fig. 2 A seven-year-old male fell from a standing height and sustained a greenstick both-bone forearm fracture (AP-**a** and lateral-**b**). The remaining cortex is in continuity but is angulated. A torsional force is typically involved with the mechanism of injury; therefore, greenstick fractures usually have a rotational component associated with the angulation. The patient underwent closed reduction and application of a sugar-tong splint (AP-**c** and lateral-**d**)

the bone exceeds its elastic limits, but not its ultimate strength. No obvious fracture line or cortical discontinuity is seen, but multiple microfractures along the length of the bow are present (Sanders and Heckman 1984a). On radiographs, an abnormal curve or narrowing of the interosseous space may be seen. The ulna is the bone that more commonly bows in the forearm after trauma. Ulnar bowing may occur in isolation, but often it is associated with a radial head dislocation (chapter ► "Monteggia Fracture Dislocation" – Fig. 1) or radial shaft fracture.

Greenstick Fracture

In greenstick fractures, one to three cortices may be disrupted on radiographs. The remaining cortex is in continuity but is angulated (Fig. 2). A torsional force is typically involved with the mechanism of injury; therefore, displaced greenstick fractures nearly always have a rotational component. Apex dorsal fractures are caused by hyperpronation, and apex volar fractures are due to hypersupination during the injury. The intact cortex helps to maintain length of the fracture and facilitates reduction.

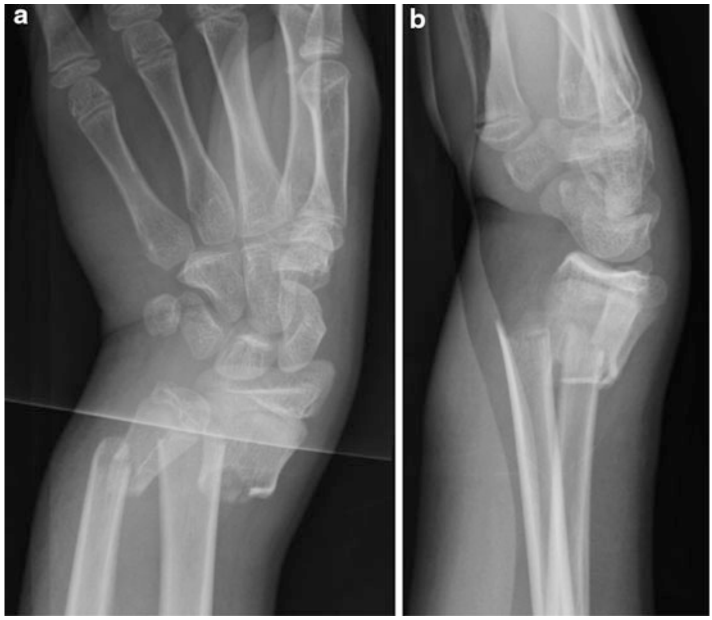

Fig. 3 A twelve-year-old male fell while skateboarding and sustained a distal third both-bone forearm fracture which was completely translated and shortened in “bayonet apposition” (AP-**a** and lateral-**b**)

Complete Fractures

Complete fractures occur when all cortical contact is lost between two fragments of bone. These fractures are further described by the fracture pattern. Transverse and short oblique non-comminuted fractures of the radius and ulna are most common in pediatric patients. Comminuted and segmental fractures are relatively uncommon, as they result from high-energy mechanisms. The most difficult fractures to reduce and cast in acceptable alignment, i.e., the most unstable fracture patterns, are both-bone complete forearm fractures. The degree of displacement of complete fractures reflects the severity of the injury and the amount of soft tissue disruption that occurs. Complete fractures may remain reasonably aligned if the periosteum and muscle attachments are not completely disrupted and stripped from the bones at the sites of fracture.

Fracture Displacement: Angulation, Translation, and Malrotation

The displacement of forearm fractures is described based on radiographic measurements of the AP and lateral radiographic projections. Angulation is determined by measuring the angle created by the fracture fragments at the apex of the deformity and is assessed separately for each bone and in orthogonal planes. Translation quantifies the amount of cortical or bony contact between the fragments. Fragments may have a percentage of bone contact, or they may be completely translated relative to one another with no end-on cortex-to-cortex contact. Additionally, fragments with no contact that then rest overlapped one on top of another are said to be in “bayonet apposition,” a reference to the shape of the swordlike weapon (Fig. 3). The degree of shortening of each bone may then be determined by measuring the length of cortical overlap.

Malrotation is more difficult to assess. Fracture fragments that are not malrotated relative to each other appear on radiographs to have similar diameters in both the AP and lateral projections. A more reliable way to assess rotation is to compare the relative positions of the bicipital tuberosity of the radius proximally and the radial styloid distally as viewed on an AP radiograph with the forearm neutrally rotated. In the normal radius, the bicipital tuberosity and the radial styloid point 180° from each other. The degree of malrotation can be estimated based on the radiographic appearance of these landmarks.

Outcome Assessment

Many studies define outcomes based on radiographic alignment of the fracture at healing and by the clinical outcome, typically determined by measuring forearm range of motion and the occurrence of complications. In order to determine more consistently the effectiveness of forearm fracture treatment methods, Flynn et al. proposed the Children's Hospital of Philadelphia Forearm Fixation Outcome Classification. In this classification, the results of fixation may be labeled as being "good," "fair," or "poor." A "good" outcome is classified as being one where the child has full range of motion (<10° loss of supination and/or pronation) and no postoperative complications. A "fair" outcome is defined as the child having minimal loss of range of motion (<30° supination and/or pronation) and/or minor, resolving postoperative complications. A "poor" outcome occurs with loss of range of motion (>30° supination and/or pronation) and/or major postoperative complications, such as infection, compartment syndrome, or delayed union (Flynn et al. 2010).

Another similar outcome assessment was described by Price et al., with categories being labeled as "excellent," "good," "fair," or "poor." To be classified as "excellent," the patient must have no complaints and a loss of range of motion <10°. "Good" results include those having mild complaints with vigorous activity and loss of motion between 11° and 30°. A result is recorded as "fair" if complaints occur with daily activities and loss of motion is between 30° and 90°. If complaints are more severe or there is greater loss of motion, the outcome is considered "poor" (Price et al. 1990).

Nonoperative Treatment

Most pediatric forearm fractures are best treated with closed reduction and long-arm cast immobilization (Zionts et al. 2005; Jones and Weiner 1999). In one study of over 730 forearm fractures, of which 300 were displaced significantly, only 22 failed initial closed reduction and casting (Jones and Weiner 1999). The trend toward operative fixation over the last 15 years has helped to define operative indications. Surgical treatment is indicated as the primary treatment for those patients with open fractures, vascular injuries, a "floating elbow," and severe soft tissue complications such as a compartment syndrome or tissue loss. Only after an unsuccessful attempt at closed fracture management is surgery indicated for the remainder of patients, with few exceptions. Certain fractures have a high risk of closed treatment failure including displaced proximal third radius fractures, displaced fractures in children over 10 years of age, and mid-diaphyseal fractures with initial ulnar angulation greater than 15° (Bowman et al. 2011). An attempt should be made to treat children and adolescents with forearm fractures nonsurgically at the outset, even if they fall into these "risk of failure" categories.

Nonoperative Management of Forearm Fractures

Indications	Contraindications
An attempt should be made to treat children and adolescents with forearm fractures nonsurgically	Vascular injury
	Open fracture
	Compartment syndrome
	Severe soft tissue injury
	"Floating elbow"

Emergency Department Management

Closed reduction and immobilization of forearm fractures is the preferred treatment option. After adequate patient assessment and review of the radiographs, the surgeon must define the degree of displacement. Children with nondisplaced or minimally displaced fractures are placed into a long-arm cast or a sugar-tong plaster splint with the elbow flexed 90° and neutral rotation of the forearm. Sedation is rarely needed and patients are discharged from the emergency department after fracture care instructions are given to the child and the family.

Analgesia/Sedation

Intravenous ketamine provides excellent sedation and analgesia enabling a closed reduction. This method induces a trancelike state that combines sedation, analgesia, and amnesia with little cardiovascular depression (McCarty et al. 1999).

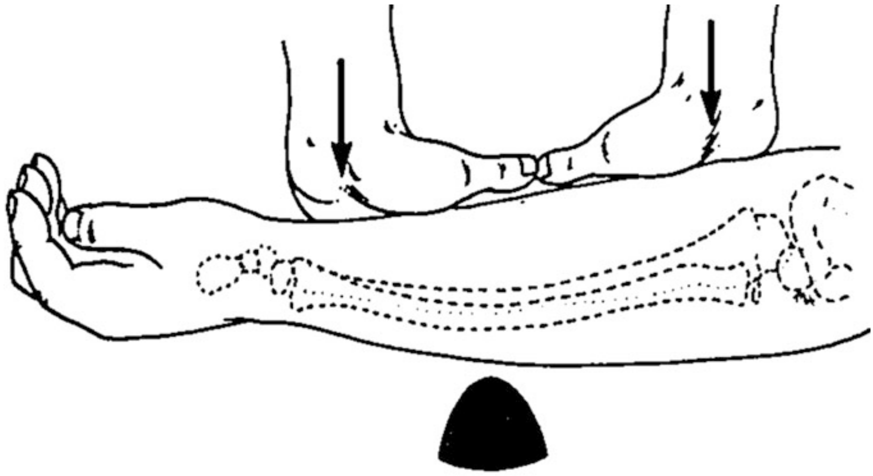

Fig. 4 Plastic deformation of the forearm may be reduced by applying gentle pressure proximal and distal to the apex of the bow while the forearm rests on a bolster or bump that acts as the fulcrum for deformity correction (From Sanders and Heckman 1984b)

Intravenous conscious sedation methods are effective for closed fracture management but demand an experienced sedation team and safety protocols. Complications, such as an adverse reaction, can occur with sedation. Therefore it is mandatory the emergency department staff be trained to properly dose medications based on the child's weight, the use of pediatric cardiovascular monitoring, and, most importantly, resuscitation techniques (Cameron et al. 2000). Other methods of analgesia for upper extremity fracture management include alternative intravenous sedation drug regimens, such as fentanyl-midazolam, and regional anesthetic techniques, such as a Bier block or axillary block. A hematoma block may be plausible for distal forearm fractures; however, this technique is less effective for proximal fractures. Also, children may be anxious and/or uncooperative, making it a challenge to inject the fracture site. One report utilized inhaled nitrous oxide to obtain sedation, and then a hematoma block was performed allowing for fracture reduction (Hennrikus et al. 1995).

Fracture Manipulation

Plastic Deformation

Fractures that are plastically deformed with an unacceptable degree of angulation can typically be managed in the emergency department. After adequate sedation and analgesia has been provided, the fractured forearm may be gently manipulated straight by three-point bending forces centered at the apex of the deformity. For small children, the physician places his or her thumb at the apex and applies steady pressure at the ends of the bone. Alternatively, a rolled towel or cushioned bump is placed on the stretcher, and the apex of the deformity is placed on top of it, allowing the physician to apply downward pressure at the bone ends and gently rock the fracture around the fulcrum over a period of 3–5 min to achieve correction (Fig. 4). The goal is not to complete the fracture but instead to restore alignment, ideally achieving anatomic alignment but generally no more than 15–20° of residual angulation (Vorlat and De Boeck 2003). After reduction, a three-point molded long-arm cast is applied. If the fracture does not reduce, operative reduction under anesthesia, either with the above technique or by percutaneous drill osteoclasis at the apex of the deformity, may be indicated (Blackburn et al. 1984).

Greenstick Fractures

Similar to plastic deformations, greenstick fractures are usually treated with a closed reduction and well-molded cast placed under conscious sedation.

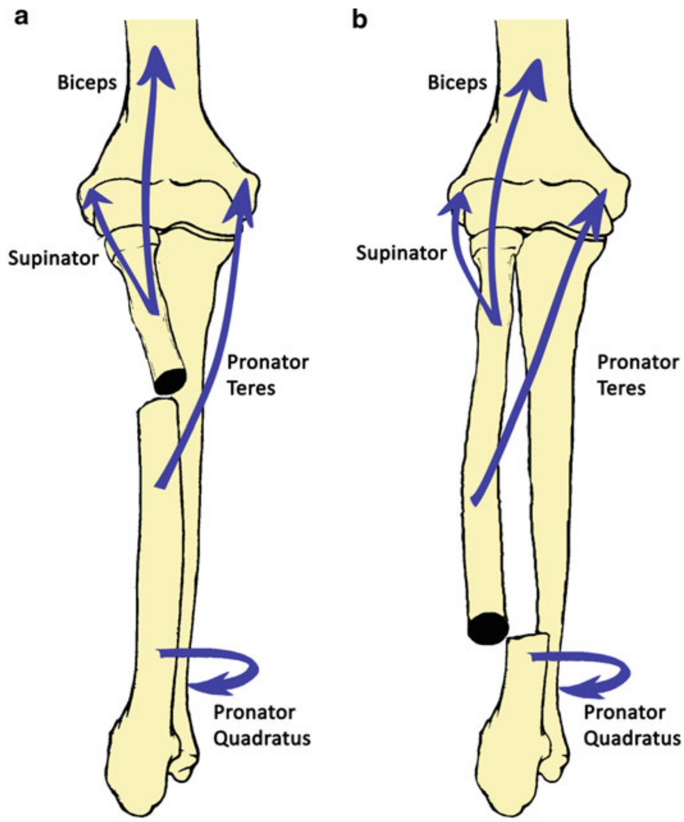

Fig. 5 Rotational displacement of the radius is caused by muscle forces acting proximal and distal to the fracture: (**a**) proximal fractures and (**b**) distal fractures (Adapted from Cruess, R.L. Orthop Clin North Am 1973; 4:969)

In order to reduce these fractures, the force opposite to the mechanism of injury is applied. As greenstick fractures result predominantly from torsional forces that occur as the arm is axially loaded, reduction is often easily achieved by merely applying gentle traction and rotating the distal forearm and thumb toward the apex of the deformity (Noonan and Price 1998), often referred to as the "rule of thumbs." Therefore, apex volar fractures are reduced by pronating the forearm while apex dorsal fractures are reduced by forearm supination. A topic of controversy when treating these fractures is whether or not the fracture should be completed. Advocates for completing the fracture argue that this will help prevent re-angulation or diminish the risk of refracture (Rang 1983). In contrast, many believe that the intact cortex helps maintain the alignment of the fracture after reduction (Alpar et al. 1981). After reduction, the arm is immobilized in a well-molded long-arm cast in neutral rotation with the elbow flexed 90°.

Complete Fractures

After adequate sedation and analgesia is achieved, longitudinal traction is applied to the forearm. This may be achieved by placing the fingers of the affected extremity in finger traps and suspending them from an intravenous pole. The weight of the arm provides a traction force allowing the fracture fragments to realign as muscle forces are overcome. Additional traction can be achieved by applying small weights to a cuff wrapped around the upper arm. Without cortical contact, the bone fragments are susceptible to displacement by muscle forces acting on the bone. Alternatively, an assistant may apply longitudinal traction across the fracture by grasping the upper arm proximally and the hand distally while the physician manipulates the bone fragments. Muscle forces influence rotation of the fragments and must be taken into account when reducing complete fractures to avoid malrotation (Fig. 5). Due to the forces of the biceps and supinator,

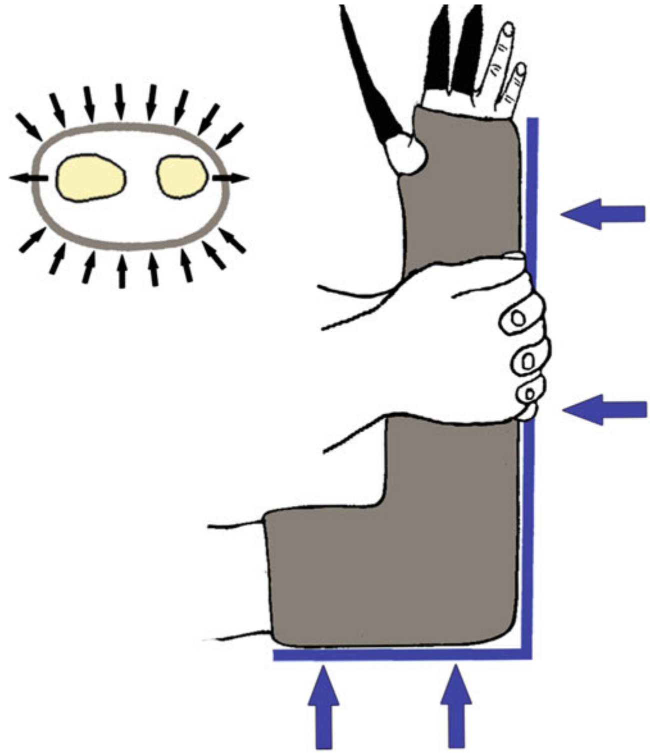

Fig. 6 Finger traps may be used to provide traction while the long-arm cast is applied. The ideal cast has an interosseous mold resulting in an oval shape in the mid-forearm combined with flat ulnar and posterior humeral borders

complete proximal radius fractures are best immobilized in supination. In the middle third of the forearm, the rotational forces are relatively balanced so neutral rotation is appropriate. For fractures of the distal third of the forearm, the pronator quadratus is acting on the distal fragment. Therefore, these fractures are best reduced and held in some pronation. The forearm should not be placed in extreme positions of supination or pronation, as significant stiffness can occur after fracture healing. A fixed supination deformity from a contracture is particularly debilitating and a challenge to manage.

Immobilization After Reduction

Careful application of a well-molded circumferential cast after reduction is critical for maintenance of alignment and to prevent complications. If there is a concern for severe swelling, the cast is bivalved and overwrapped with an elastic bandage prior to discharge or the child is admitted and observed overnight. Alternatively, the child may initially be placed into a non-circumferential splint, such as a sugar-tong splint (Younger et al. 1997), and casted upon outpatient follow-up. The ideal long-arm cast applied to treat forearm fractures must have a three-point mold about the fracture sites and be oval in shape at the middle of the forearm with an indent between the radius and ulna to create an interosseous mold. The upper arm part of the cast should be tapered just above the supracondylar area of the humerus, and the ulnar and posterior humeral borders should be essentially flat to limit the distal migration or shifting in the cast (Fig. 6).

Acceptable Reduction

After cast application, high-quality AP and lateral radiographs are taken and analyzed. Acceptable reduction parameters vary based on the chronological age and, more importantly, the estimated years of growth remaining, the location of the fracture, and the postreduction alignment. The ideal reduction parameters that reliably yield satisfactory clinical results are controversial. Even small degrees of residual angulation have been correlated with some loss of forearm rotation (Alpar et al. 1981; Noonan and Price 1998; Kasten et al. 2003). In addition to bony malunion, soft tissue fibrosis, especially about the interosseous membrane, may lead to limited forearm motion after fracture healing (Nilsson and Obrant 1977). Angulation of the radius, especially when the radial bow has been lost, correlates with loss of forearm rotation while ulnar angulation has a greater influence on the cosmetic or aesthetic appearance of the forearm (Dumont et al. 2002). For children under the age of 8 years, up to 20° of diaphyseal angulation may remodel while angulation of as little as 10° may not in those older than 10 years of age (Jones and Weiner 1999). To confound the issue, residual radiographic angulation does not always have a direct correlation with functional outcomes and patient satisfaction (Price et al. 1990). Shortening is well tolerated in patients younger than 10 years of age, with up to one centimeter being acceptable after failed closed reduction (Do et al. 2003). Even fractures in bayonet apposition treated with casting and no analgesia, sedation, or a formal reduction can result in excellent clinical outcomes (Crawford et al. 2012).

Children Younger than 10 Years of Age

The recommended acceptable forearm reduction parameters for children younger than 10 years of age include residual angulation of the radius or ulna measuring 20° or less. There are two exceptions: radius fractures in the proximal third and radius fractures with apex ulnar angulation. Proximal radius fractures with angulation of 10° or more and radius fractures with any apex ulnar angulation are at risk of rotation loss even in this young age group. Complete translation, bayonet apposition with shortening of 1 cm or less, and malrotation less than 30° are other acceptable parameters of reduction.

Children 10 Years of Age and Older

Children who are 10 years of age and older have less capacity for fracture remodeling. Greater than 10° of angulation of either bone in any plane, greater than 50 % translation, shortening or bayonet apposition, and greater than 30° of malrotation are unacceptable reduction parameters. Individuals with less than 2 years of growth remaining have minimal remodeling capability; therefore, near-anatomic alignment must be obtained for acceptable reduction.

Complications of Nonoperative Treatment

Stiffness

The most common complication to occur after a forearm shaft fracture is significant forearm stiffness, with a decrease in pronation more common than loss of supination (Högström et al. 1976; Holdsworth and Sloan 1982). This most commonly occurs in patients with malunited fractures but may occur even after anatomic healing. Avoiding extreme positions of either pronation or supination in a cast and permitting motion as soon as fracture healing occurs are some ways to limit functional loss of rotation after cast treatment of forearm fractures.

Malunion

Malalignment after healing occurs in 10–25 % of patients (Davis and Green 1976). This complication is cast related and mostly due to poor molding after acceptable reduction. Occurrence of this complication can often be remedied by repeating the closed reduction and casting (Davis and Green 1976; Voto et al. 1990). A small percentage of children will experience a malunion, but the deformity is mostly cosmetic and may or may not cause loss of functional forearm motion (Daruwalla 1979). Close follow-up with serial AP and lateral radiographs within the first 2 weeks postreduction is critical to prevent this complication. Cast wedging may be used to improve unacceptable angulation if it is noticed in a timely manner. Osteotomies of the radius and ulna are salvage options for those patients with healed malunions (Price and Knapp 2006).

Refracture

Diaphyseal forearm fractures are the number one location of refracture in children, with most occurring at the original site (Landin 1997). Up to 8 % of patients will experience a refracture. Children are at highest risk for this complication up to 1 year following union of the initial fracture; refractures are much less common during splint wear (Chung and Spilson 2001). Most refractures occur in the proximal and distal third of the forearm (Baitner et al. 2007).

Uncommon Complications

Delayed union and nonunion are very rare complications. Nonunion occurs most commonly in the ulna in patients between 13 and 16 years old (Adamczyk and Riley 2005). Synostosis, although rare, may result in complete loss of forearm rotation. Compartment syndrome is rare after closed reduction and cast treatment of forearm fractures but must be suspected if a child is not comfortable 3–4 hrs postreduction (Crawford 1991). A non-circumferential splint may be applied or the cast may be bivalved. The treatment for compartment syndrome is emergent fasciotomies. Finally, cast complications may occur. Skin breakdown, skin burns from hot dipping water, and cuts and/or burns from the cast saw occur but are easily preventable if proper techniques are utilized (Halanski and Noonan 2008). Refer to Table 1 for tips on safe fiberglass cast application.

Table 1 Pearls for safe and effective fiberglass cast application

Avoid excessive padding to enhance molding and reduce the risk of loss of fracture reduction
Maintain joints in the same position while applying cast to avoid pressure points at joint creases
Use cool dipping water to avoid excessive heat generation and potential burns under the cast
Use stretch-relaxation of the fiberglass to avoid excessive cast constriction after cast curing
Do not trim or bivalve fiberglass cast until it has cooled to avoid cast saw burns of the skin

Part B: Operative Treatment

Indications

Fractures of the forearm are typically treated successfully with closed reduction and cast immobilization. Surgical treatment is indicated for open fractures (Greenbaum et al. 2001; Luhmann et al. 2004), severe soft tissue injury or compartment syndrome, vascular injuries, and floating elbow injuries (ipsilateral fractures of the distal humerus and forearm) (Ring et al. 2001). The inability to obtain acceptable alignment via a closed reduction necessitates surgical reduction and fixation. Also, unstable fractures that have lost alignment at follow-up may require repeat closed reduction or operative fixation.

Surgical Procedures

Options for surgical treatment include closed or open reduction and intramedullary nailing, open reduction and internal fixation utilizing plates and screws, and in rare circumstances external fixation. Intramedullary nailing has become the standard operative treatment method for skeletally immature patients and has demonstrated good results (Lascombes et al. 1990; Till et al. 2000; Flynn et al. 2010; Martus et al. 2013).

Intramedullary Nailing

Preoperative Planning

Intramedullary nailing can be done percutaneously or with minimal surgical exposure using flexible nails (1.5–2.5 mm diameter) or smooth wires/pins (0.062 or 5/64th inches diameter). The nail diameter should fill approximately two thirds of the canal isthmus. The implant is advanced across the fracture site via a closed or limited open reduction. Dual bone fixation is most common, but occasionally single-bone fixation provides adequate stabilization of the fracture reduction.

Positioning

The patient is positioned supine and general anesthesia is provided. A radiolucent hand table is

Table 2 Preoperative planning for intramedullary nailing of radius and ulna shaft fractures

OR table	Standard OR table with radiolucent hand table on operative side
Position	Supine with the patient located close to the edge of the OR table to provide sufficient mobilization of the operative extremity and unobstructed fluoroscopic visualization
Fluoroscopy	Positioned at the distal end of the hand table
Tourniquet	Non-sterile; placed on upper arm close to the axilla
Draping	Ensure the elbow, forearm, and hand are accessible
Equipment	(a) Flexible nails (1.5–2.5 mm diameter) or smooth wires (0.062 or 5/64th size)
	(b) Drill or awl
	(c) T-handled chucks
	(d) Nail bender
	(e) Small fragment set if open reduction is needed

used to support the operative extremity. A non-sterile pneumatic tourniquet is placed on the upper arm, ensuring access to the elbow. The extremity is then draped and prepped in sterile fashion including the elbow, forearm, and hand. Fluoroscopy is stationed at the distal end of the hand table. Prior to draping, the adequacy of imaging should be assessed (Table 2).

Approach

Antegrade and retrograde intramedullary nailing techniques have been described for the ulna, while retrograde nailing is standard for the radius. The order of bone fixation is variable between surgeons and may be determined based on which bone is the most difficult to reduce and most unstable. The ulna is the first bone to be nailed, as it is classically easier to reduce.

Technique

Antegrade nailing is utilized for the ulna, with insertion across the olecranon apophysis. The antegrade insertion site is directly posterior to the olecranon, which provides a direct path to the canal. Alternately, insertion can be done through the metaphysis just distal to the apophysis on the lateral aspect of the ulna (anconeus starting point). Significant complications have not been reported with either entry site.

The tourniquet can be kept deflated during fixation of the ulna if an open reduction is not required. A small incision is made over the tip of the olecranon process. Fluoroscopic guidance is used to drill a starting hole across the apophysis into the intramedullary canal. A flexible nail is inserted using a T-handled chuck. Alternatively, if a smooth wire/Steinmann pin is used, the sharp end can be used to drill the starting point and then advanced. The nail or wire is positioned just shy of the fracture site; traction is applied and a closed reduction obtained. The implant is moved past the fracture site until the far tip terminates in the distal metaphysis of the ulna. Sufficient length should be allotted for the implant to be tamped into final position, ensuring it does not violate the distal physis of the ulna. This is done by advancing the nail to its final position and then withdrawing it 1–2 cm. The nail is cut to the appropriate length and gently readvanced to its final position. The cut proximal end should terminate beneath the skin. Some surgeons may elect to leave the implant percutaneous for early removal in the office setting, but this can be challenging for younger patients (Table 3).

Attention is then directed to the radius, which is fixed in a retrograde fashion. If the tourniquet has yet to be inflated, the limb is exsanguinated and the tourniquet is inflated. The dorsal physeal sparing entry site is located at the proximal aspect of Lister's tubercle. This location is approached utilizing a 1–2 cm longitudinal incision approximately 1 cm proximal to the distal radial physis in the midline of the metaphysis between the third and fourth dorsal extensor compartments. Fluoroscopy may be used to confirm proper placement of the incision proximal to the physis. Dissection is continued through the retinaculum, and the interval between the third and fourth dorsal extensor compartments is used to expose the distal radius at Lister's tubercle. Transposition of the extensor pollicis longus tendon may be necessary for a safe starting point. Alternatively, a lateral entry point may be used via the floor of the first dorsal extensor compartment. An awl or drill is

Table 3 Surgical steps for intramedullary nailing of the ulna

Flex the elbow to 90°
Fluoroscopy used to confirm location of apophyseal starting point – in line with intramedullary canal of the ulna
1 cm longitudinal incision over olecranon followed by blunt dissection down to bone
2.7 or 3.2 mm drill or awl used to penetrate the cortex
Insert nail using T-handled chuck and advance to fracture site
Combine traction and rotation, also anterior/posterior compression if needed, to obtain reduction
Advance nail past fracture to appropriate length in distal ulna
Confirm ulnar styloid and coronoid process are 180° from each other on full-length lateral fluoroscopic image
Withdraw the nail 1–2 cm, cut the nail leaving 1–2 cm proud, and then impact the nail to final position
Close the skin with absorbable sutures and apply Steri-Strips

Table 4 Surgical steps for intramedullary nailing of the radius

Pre-contour the nail into a "C" shape
Inflate tourniquet if needed
Palpate Lister's tubercle on the distal radius
Fluoroscopy used to identify dorsal starting point 1 cm proximal to physis at the base of Lister's tubercle
1–2 cm longitudinal incision to expose radius between the third and fourth dorsal extensor compartments
Take care to protect the extensor tendons and be aware of the superficial radial sensory nerve
2.7 or 3.2 mm Drill or Awl used to penetrate the dorsal radius cortex perpendicular to the bone
"Drop your hand" (aiming drill/awl more proximal) to enlarge hole obliquely at a 30° angle
Insert the nail using T-handled chuck; point the tip directly into the hole while ensuring the extensor tendons are not interposed
Within the canal, rotate the nail 180° to align the tip parallel to the shaft of the radius
Advance the nail to the fracture site and then obtain reduction
Advance the nail past the fracture, rotating the nail as needed to optimize radial bow
Position the end of the nail just distal to the radial neck physis
Confirm radial styloid and bicipital tuberosity are 180° from each other on full-length AP fluoroscopic image
Withdraw the nail 1–2 cm, cut the nail leaving 1–2 cm proud, and then impact the nail to final position
Ensure the nail tip protrudes beyond extensor tendons into the subcutaneous tissue
Close the skin with absorbable sutures and apply Steri-Strips

used to create a unicortical entry hole after fluoroscopic verification of the planned insertion position. The hole is enlarged at a 30° angle by directing the drill or awl proximal obliquely across the radius. Once the starting point has been created, the flexible nail or smooth wire is pre-contoured to a gentle "C" shape to accommodate the radial bow. Direct visualization of the bone surface is needed to prevent tendon injury during insertion and advancement. The implant is positioned just shy of the fracture site. A closed reduction is performed, and the nail is moved across the fracture ensuring the contour of the nail is aligned with the bow of the radius. The nail should be advanced to its final position short of the radial neck physis. Subsequently, the nail is withdrawn 1–2 cm, cut to its proper length and tamped into final position. It is important to verify the cut end is not abrading the extensor tendons. Once the tendons are visualized as being away from the cut nail, the incision is closed with the implant tip beneath the skin (Table 4). A nail or wire placed using a lateral starting point can be left percutaneous for office removal. Figure 7 exemplifies a standard both-bone forearm fracture treated with flexible intramedullary nails, and Fig. 8 demonstrates a similar fracture treated with K-wire fixation using a radial styloid starting point.

Single-Bone Fixation

Surgical treatment of both-bone forearm fractures using singular bone fixation with plate and screws or an intramedullary device has been reported with good outcomes (Flynn and Waters 1996; Kirkos et al. 2000; Bhaskar and Roberts 2001; Myers et al. 2004). Either the ulna or radius can be stabilized. The relatively straight intramedullary canal of the ulna allows for easier fixation. After single-bone fixation of the ulna,

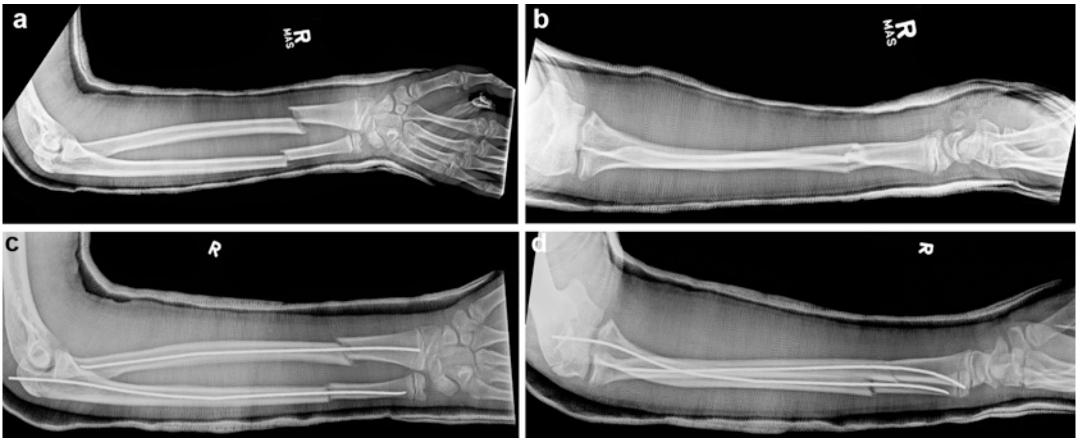

Fig. 7 A fifteen-year-old male sustained a fracture of his forearm while playing football (AP-**a** and lateral-**b**). He underwent closed reduction and casting in the emergency room. The reduction was unsuccessful, and he subsequently underwent flexible intramedullary nail fixation (AP-**c** and lateral -**d**)

Fig. 8 A ten-year-old female sustained a displaced midshaft both-bone fracture when she fell off her bike (AP-**a** and lateral-**b**). One week after closed reduction, the fracture had lost alignment (AP-**c** and lateral-**d**). She subsequently underwent intramedullary nailing of both bones using smooth K-wires, which were inserted through the radial styloid and olecranon apophysis (AP-e and lateral-f). The radius required a limited open reduction

adequate reduction is confirmed for both bones, and if the radius is stable, then it may be left without an implant. Figure 9 demonstrates a both-bone forearm fracture treated with singular fixation of the ulna.

Pitfalls and Prevention

Conversion to an open reduction of either the ulna or radius should be done to prevent risk of compartment syndrome if repeated closed manipulations fail. Approximately 5–10 min should be

Fig. 9 A thirteen-year-old sustained an unstable midshaft both-bone forearm fracture (AP-**a** and lateral-**b**) while skateboarding. After a failed attempt at closed reduction and casting, he was treated in the operating room with closed reduction and single-bone fixation of the ulna using a smooth K-wire. The radius reduced anatomically and was stable after ulnar fixation, therefore fixation of the radius was unnecessary

allotted for closed manipulation of each bone before open reduction is recommended. One third of closed forearm fractures treated with intramedullary nailing require an incision at the fracture site to achieve a reduction and facilitate nail passage (Flynn et al. 2010; Martus et al. 2013). Open reduction of the ulna is performed utilizing a 1–2 cm incision made on the subcutaneous border of the ulna at the fracture site. The radius is opened in a similar manner using a small volar incision for distal and middle third fractures. Proximal third radius fractures can be approached via a volar incision, although some surgeons prefer a dorsal approach. After exposing the bone fragments, each end is grasped with bone-holding forceps and reduced manually. An assistant may be needed to provide simultaneous traction and/or rotation. Alternatively, a freer elevator can be placed in the fracture and utilized to lever the fragments to permit reduction.

Malrotation of the fracture site must be avoided intraoperatively. Anatomic landmarks can be used to ensure proper rotation is achieved during fracture reduction. The bicipital tuberosity of the radius should be oriented 180° from the radial styloid on a fully supinated AP radiograph of the forearm. The bicipital tuberosity faces medial and the radial styloid lateral. The ulna can be similarly evaluated on a lateral radiograph of the forearm using the coronoid process and ulnar styloid. The coronoid is positioned volarly 180° in relation to the ulnar styloid, which is dorsal.

Incarceration of a nail within the intramedullary canal may result in distraction of the fracture site and cause malrotation. Removing the nail and choosing a smaller diameter will allow for easier passage within the canal and improve alignment of the fracture. A downside of reducing the diameter of a titanium nail is that the rigidness is also decreased. Stainless steel nails are stiffer and can be utilized when a smaller diameter nail is required for stabilization.

Attritional rupture of extensor tendons is a risk of intramedullary nailing. The extensor pollicis longus should be transposed during the approach for the dorsal insertion site on the radius to prevent possible rupture (Table 5).

Postoperative Care

Immobilization options include either a sugar-tong plaster splint or long-arm fiberglass cast which should be bivalved to accommodate swelling. At the 1-week post-op visit, a splint is converted to a cast or the bivalved cast is circumferentially overwrapped with fiberglass. Duration of immobilization and timing of hardware removal is variable between surgeons. Multiple aspects play a role in the decision process including the risks of stiffness, refracture, percutaneous pin complications, or hardware irritation. Six to eight weeks of cast

Table 5 Potential pitfalls of surgery and pearls for prevention: intramedullary nailing of radius and ulna shaft fractures

Unable to achieve closed reduction	Conversion to a mini-open reduction should be done without hesitation to prevent risk of compartment syndrome. Typically, no longer than ten minutes is spent attempting a closed reduction
Fracture is malrotated and/or distracted	Carefully evaluate full-length forearm AP and lateral fluoroscopy images to assess the 180° relationship of the bicipital tuberosity to the radial styloid, as well as the coronoid process to the ulnar styloid
	Consider backing out the nail and adjusting the rotation of the forearm and/or nail. Then readvance the nail
Unable to advance nail through the isthmus	Be sure the nail is not incarcerated in the canal causing distraction and/or malrotation. If so, then remove the nail and choose a smaller-diameter-sized nail
	If a 1 mm titanium nail is too flexible, consider using a stainless steel nail
Extensor pollicis longus (EPL) is in the way of your starting point	Transpose the EPL tendon to minimize the risk of attritional rupture

immobilization is recommended with removal of buried implants no sooner than 3 months postoperatively, in the operating room. Implants may require earlier removal due to local irritation particularly at the olecranon bursa. Any complaints of difficulty or pain with thumb extension should prompt immediate removal of the radial nail with exploration of the EPL tendon. Care should be taken with early removal for concerns of refracture. Nails or wires/pins left outside the skin should not remain in place longer than 6 weeks and, for the cooperative child, can be removed in the office (Table 6).

Table 6 Postoperative protocol for intramedullary nailing of radius and ulna shaft fractures

End of surgery	Immobilize in sugar-tong plaster splint or long-arm bivalved fiberglass cast
1-week follow-up	Check AP and lateral forearm radiographs
	Convert splint to long-arm fiberglass cast or overwrap bivalved cast
Duration of immobilization	*6–8 weeks:*
	First 4 weeks in a long-arm cast
	Next 2–4 weeks in a short arm cast or sugar-tong splint
	After removal of cast and confirmation of complete radiographic healing, the patient may be weight-bearing as tolerated and return to full activities
Radiographs	1 week, 4 weeks, 8 weeks, 12 weeks postoperatively; longer if full union is not present
Hardware removal	3–6 months

Plate and Screw Fixation

Patients who are skeletally mature or near skeletal maturity are usually treated with plate fixation. Additionally, some younger children may require initial plate fixation if there is significant fracture comminution or an inability to maintain adequate reduction with an intramedullary implant, typically occurring in cases of a high-energy injury. Figure 10 demonstrates a fracture treated in an adolescent female, following a high-energy fall, with an unstable fracture pattern. Late indications for plating are nonunions or an impending malunion with abundant callus formation which may block nail passage due to closure of the medullary canal. The volar approach of Henry is used for plating distal and midshaft fractures of the radius. Occasionally, a dorsal Thompson approach may be necessary for proximal radius fractures. The ulna is exposed utilizing an incision along the subcutaneous border between the extensor carpi ulnaris and flexor carpi ulnaris. Typically, 3.5 mm dynamic compression plates (DCP) are used although smaller plates may be utilized for young children, such as 2.7 mm compression plates (Fig. 11). One third tubular plates are also an option.

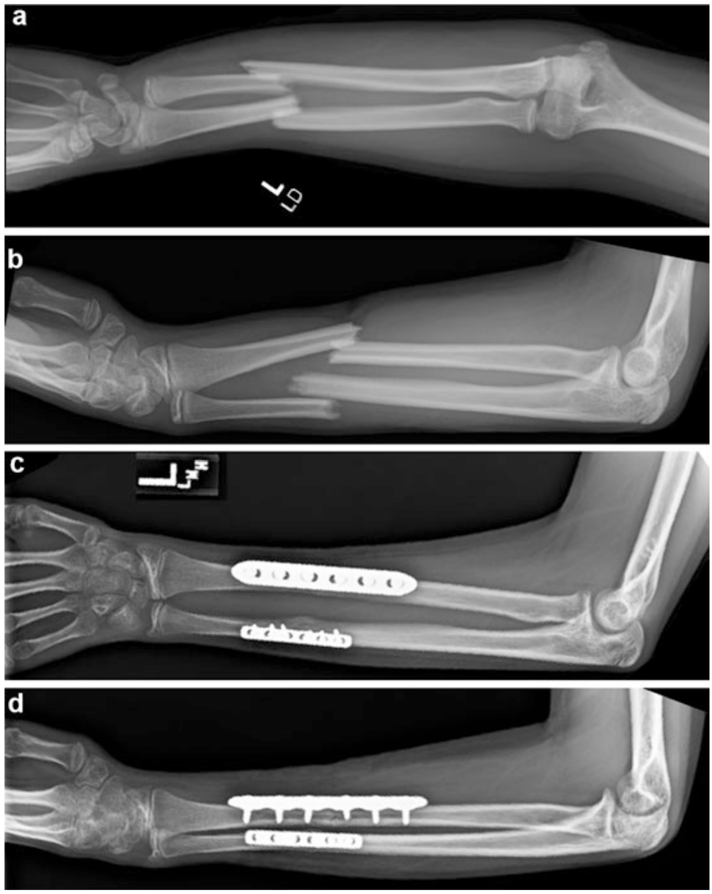

Fig. 10 A fourteen-year-old female sustained a both-bone forearm fracture from a fall off the uneven bars during gymnastics (AP-**a** and lateral-**b**). She underwent open reduction and mini fragmentary plate fixation, the surgeon's preference (AP-**c** and lateral-**d**)

External Fixation

External fixation of forearm fractures in children is rarely indicated and typically not used for definitive management. Severe soft tissue damage, wound contamination, or segmental bone loss may necessitate the use of external fixation as a temporary treatment. Half-pins 3.5 mm in size or smaller are used to build the construct. Ulna pins can be inserted along the subcutaneous border of the entire bone. Fluoroscopy should be used to confirm bicortical fixation and ensure pin tips are not too deep in the central region of the forearm placing neurovascular structures at risk. Radial pins should be placed with caution especially in the proximal forearm. If stabilization is needed in this region, a small incision should be used along the lateral side with gentle dissection to the radius. This will ensure safety of the posterior interosseous nerve before pin placement. Distally pins can be placed in an oblique lateral position or directly posterior, utilizing a small incision to ensure injure to the extensor tendons or superficial radial sensory nerve does not occur. As with the ulna, fluoroscopy must be used to visualize pin depth in the radius.

Complications of Surgical Treatment

IMN Versus ORIF?

Several studies have compared intramedullary nailing to open reduction and internal fixation of forearm fractures, without a significant difference in functional outcomes being noted. Complication rates vary with no statistical benefit of one

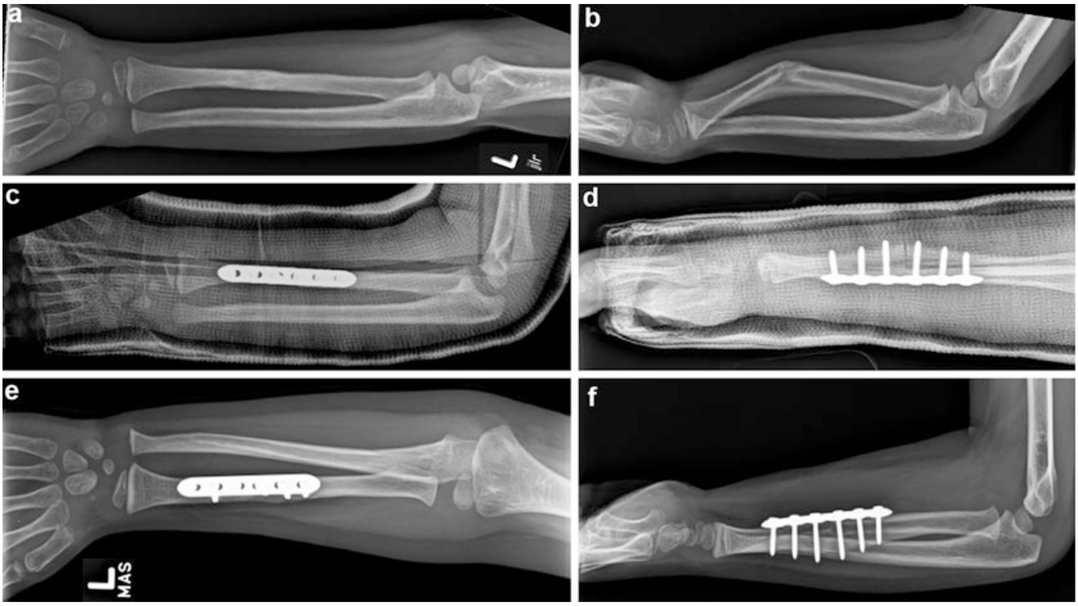

Fig. 11 A five-year-old male presented 6 months after casting for a midshaft radius and ulna fracture. He had a visible forearm deformity and severely limited forearm rotation. Radiographs revealed a malunion of the radius with 40° of dorsal angulation (AP-**a** and lateral-**b**). Due to the concern that the deformity was too large for effective remodeling to occur, he underwent a corrective osteotomy using small fragmentary fixation (AP-**c** and lateral-**d**). He healed uneventfully (AP-**e** and lateral-**f**) and 6 months after surgery had normal forearm rotation

technique over the other (Van der Reis et al. 1998; Fernandez et al. 2005; Smith et al. 2005; Ozkaya et al. 2008; Reinhardt et al. 2008; Teoh et al. 2009). The incidence of complications for intramedullary nailing is 6–42 % compared to 12–33 % for open reduction and internal fixation. Combined data indicates that nonunions are rare events with only a 0.2 % (1/351) rate after intramedullary nailing, and a 4 % (4/95) rate after open reduction and internal fixation (Van der Reis et al. 1998; Fernandez et al. 2005; Smith et al. 2005; Ozkaya et al. 2008; Reinhardt et al. 2008; Teoh et al. 2009; Martus et al. 2013). Delayed union for intramedullary nailing occurred in 5 % (19/351) of patients from seven studies, compared to 1 % (1/95) of patients in six series having undergone open reduction and internal fixation (Van der Reis et al. 1998; Fernandez et al. 2005; Smith et al. 2005; Ozkaya et al. 2008; Reinhardt et al. 2008; Teoh et al. 2009; Martus et al. 2013). Intramedullary nailing has demonstrated better cosmetic results (Fernandez et al. 2005; Teoh et al. 2009).

Intramedullary Nailing

Complications following intramedullary nailing include refracture, compartment syndrome, delayed union, infection, neurovascular injury, synostosis, and tendon injury. Refer to Table 7 for a summary of complications and management recommendations.

Refracture after intramedullary nail removal or even with implants in situ has been reported to occur 4 % of the time, similar to the rate of those treated nonoperatively. Refracture with nails already in place have been successfully treated with closed reduction (Muensterer and Regauer 2003; Martus et al. 2013). Prevention of refracture is best accomplished by removing hardware only after sufficient healing has occurred. This motivates some surgeons to wait 6–12 months for nail removal. No matter the chosen timeline for removal, afterward, a removable splint should be utilized for a short period to provide protection.

Compartment syndrome associated with intramedullary fixation has an incidence ranging

Table 7 Complications of radius and ulna shaft fractures treated with intramedullary nailing

Complications	Management
Refracture	Refracture after closed treatment should be managed with surgical intervention
	Refracture with nails already in place may be successfully managed with closed reduction
	Prevention of refracture can be minimized by ensuring adequate healing prior to hardware removal
	A short period of immobilization with a removable splint is recommended after removal of hardware
Compartment syndrome	Fasciotomies should be performed
	High-energy injuries, multiple attempts at closed reduction, and multiple attempts at nail passage are all risk factors
Delayed union/ nonunion	Rare in the pediatric population especially those treated nonoperatively
	Higher rates are associated with older patients, open treatment, and open fractures; therefore, infection should be ruled out first
	Delayed unions can be monitored
	Intramedullary nailing should be converted to compression plating with bone grafting as needed for nonunions
Synostosis	After maturation at 6 months to 12 months, excision can be performed
	Consider interposition of fat or inert material (bone wax) for prevention
Infection	Treatment should be focused on the severity, requiring either antibiotics, removal of hardware, or irrigation and debridement
Neuropraxia	Complete recovery can typically be expected
	EMG may be considered if no signs of recovery are seen by 3 months
	Nerve exploration/decompression/ possible repair can done for individuals who fail to recover normal function within a satisfactory time period
EPL rupture	Can be avoided with transposition
	EIP to EPL transfer can restore function

from 1.6 % to 10 %. Higher rates have been associated with open fractures and increased operative times. The authors hypothesize that multiple attempts at closed reduction and/or multiple passes with the intramedullary nail may increase the risk of compartment syndrome (Yuan et al. 2004; Martus et al. 2013; Blackman et al. 2013). Parents and patients should always be advised that there is a potential for this complication intraoperatively or postoperatively and that a fasciotomy will be required if compartment syndrome is suspected.

Delayed union is defined as incomplete consolidation at about 12 weeks, and a nonunion is incomplete healing by 6 months (Schmittenbecher et al. 2008). A delayed union after intramedullary nailing of pediatric forearm fractures is associated with children older than 10 years, fixation of the ulna, open reduction required to pass the nail, and open fractures (Schmittenbecher et al. 2008; Fernandez et al. 2009; Flynn et al. 2010; Lobo-Escolar et al. 2012), although recently a single study demonstrated no correlation of delayed union with open fractures, open reduction, or fixation of the ulna (Martus et al. 2013). Radioulnar synostosis following intramedullary nailing is rare, occurring in only 3/225 cases between two studies (Cullen et al. 1998; Martus et al. 2013).

Superficial infection has been reported to occur in up to 5 % of cases following intramedullary nailing. Deep infection is rare with a range of 0.2–1 % occurrence, with greater rates noted for patients with open fractures (Lascombes et al. 1990; Richter et al. 1998; Flynn et al. 2010; Martus et al. 2013). Treatment should be focused on the severity, understanding that patients may require antibiotics, removal of hardware, irrigation and debridement, or a combination of these.

Transient neuropraxia is the most common form of nerve injury, usually involving the superficial radial sensory nerve. The incidence is 2–3 % and can occur with either a dorsal or lateral approach to the distal radius when inserting a nail into the radius (Martus et al. 2013). Ulnar nerve injury has also been reported, which resolves spontaneously (Luhmann et al. 2004).

Extensor tendon injury is possible with intramedullary nailing of the radius. Primarily, the extensor pollicis longus (EPL) is damaged, with

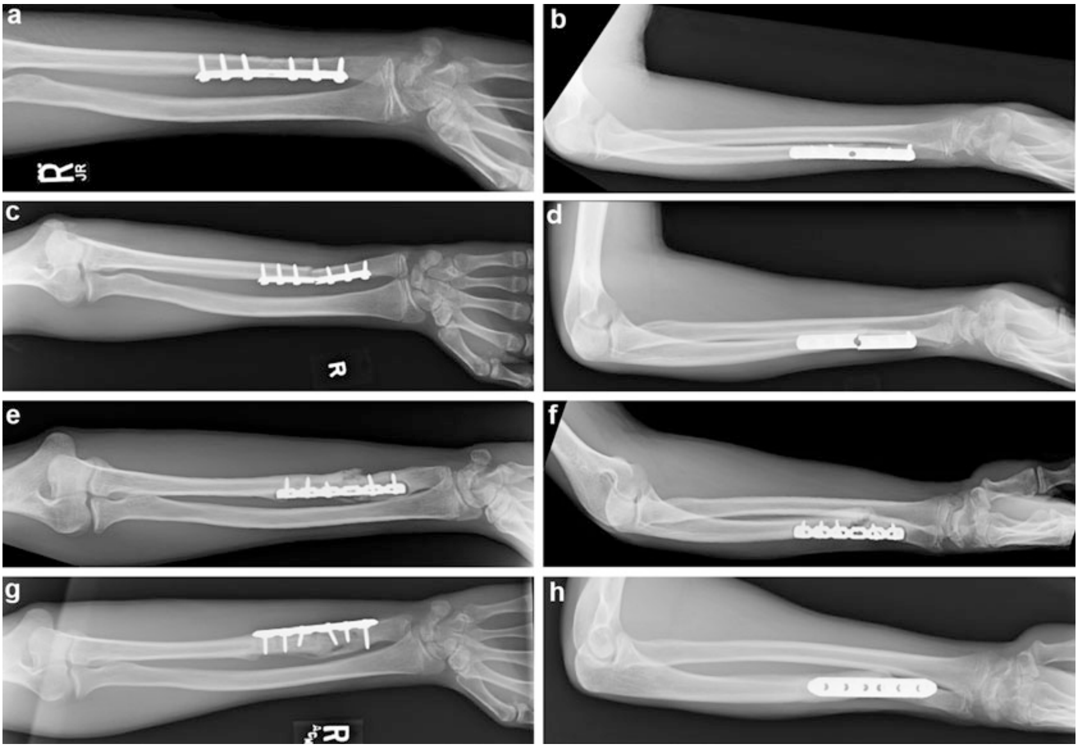

Fig. 12 A seventeen-year-old male had open reduction internal fixation for an isolated ulnar shaft fracture using a 1/3 tubular plate (AP-**a** and lateral-**b**). Four months later the fracture had not united and the implant failed (AP-**c** and lateral-**d**). Seven months after revision with a reconstruction plate, the patient returned to the clinic with persistent pain and incomplete union (AP-**e** and lateral-**f**). He underwent a third surgery with hardware revision and bone grafting. This time an LC-DCP plate was utilized and the fracture went on to complete union (AP-**g** and lateral-**h**)

rupture rates of 1–2 % (Flynn et al. 2010; Martus et al. 2013). The dorsal entry site places the EPL at greater risk compared to the lateral entry site. Incisions should be made large enough to protect the tendon(s) from harm during insertion of the nail and at the time of nail removal. Ideally, the nail should be cut flush with the bone, but subsequent removal may be quite challenging. Therefore, nails left proud should not encroach upon the extensor tendons as they may lead to risk of an attritional rupture. The EPL tendon can be transposed away from Lister's tubercle to minimize the risk of injury, and/or the nail can be left superficial to the tendons.

ORIF

Similar complications are noted for plate fixation with additional concerns for implant-related fractures and a higher risk of radioulnar synostosis, especially if the procedure is performed through a single incision. Pediatric bony anatomy may not accommodate fixation with 3.5 mm compression plates; therefore, 2.7 mm plates or even 1/3 tubular plates can be considered. However, 1/3 tubular plates may not provide sufficient strength and grossly fail, especially if the fracture progresses to a delayed union and/or the patient is nearing skeletal maturity (Fig. 12).

The need for removal of plates after bony union continues to be a debated topic. Survivorship of forearm plates at 10 years has been reported to be 85 % (Clement et al. 2012). Although retained plates have minimal reported complications, there is a risk of fracture due to an inherent stress riser present at the proximal and distal aspect of the plates. This creates the potential for peri-implant fractures. On the other hand,

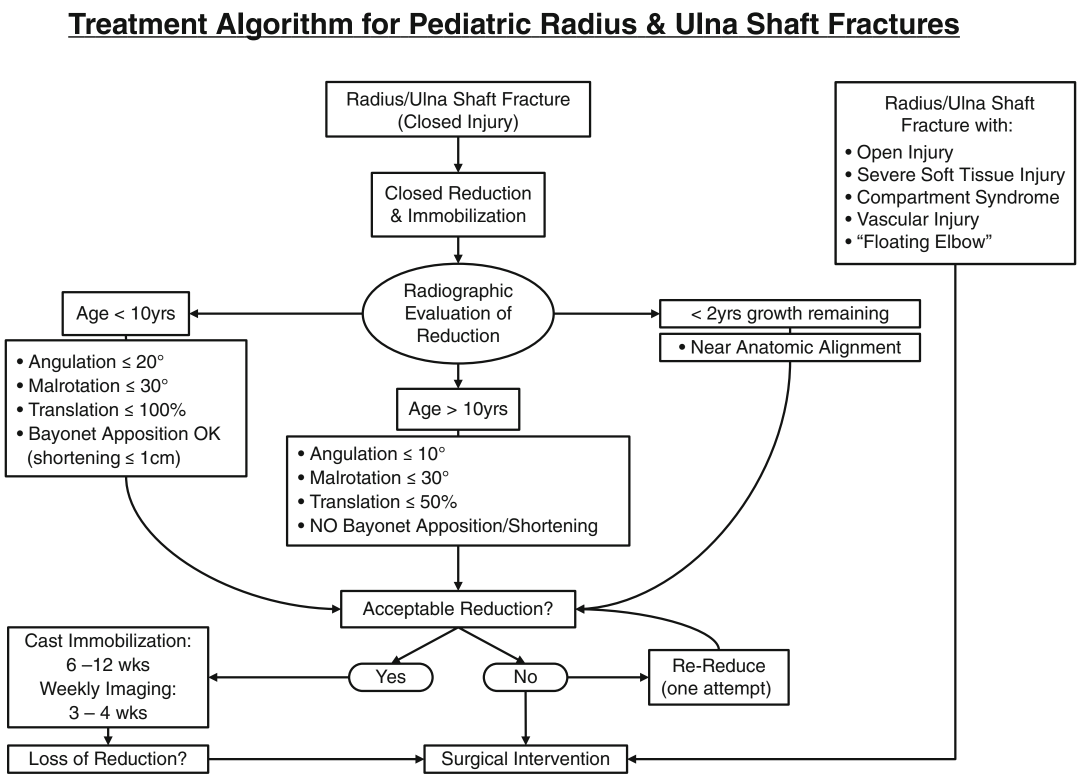

Fig. 13 Closed reduction and immobilization is the preferred treatment for pediatric forearm shaft fractures. The reduction parameters outlined in the algorithm are focused on age and growth remaining

there is also a chance of refracture after plate removal. Interestingly, dynamic compression plates have shown approximately a 7 % rate of peri-implant fractures and a 7 % rate of refracture after plate removal. In contrast there was only a 1 % risk of peri-implant fracture with a 1/3 tubular plate and no refractures reported after removal. There were also no frank hardware failures (Kim et al. 2005; Clement et al. 2012). Also, growing children may engulf the plate with bone. This can impede later hardware removal or hinder treatment of a secondary fracture. Other concerns with plate retention include possible bacterial colonization and theoretical risk of carcinogenicity from metal corrosion or metallic allergy (Peterson 2005). The benefits of plate removal should be weighed against the complications of the surgical procedure. In the adult population, a 40 % complication rate has been associated with forearm plate removal (Langkamer and Ackroyd 1990). This rate is 9 % in the pediatric population (Kim et al. 2005).

Preferred Treatment

Closed reduction and immobilization is the preferred treatment for pediatric forearm shaft fractures. The reduction parameters outlined in the algorithm (Fig. 13) are focused on age and growth remaining. After inadequate reduction in the acute setting, a single repeated attempt to achieve an acceptable reduction is recommended. If this fails, surgical intervention is warranted. A subset of fractures are at greater risk for forearm rotation loss in patients less than 10 years old. These include proximal radius fractures with angulation of 10° or more and radius fractures with any apex ulnar angulation. Therefore, surgical fixation is considered for these fractures. Flexible intramedullary nailing is the preferred technique for surgical treatment of radius and ulna shaft fractures. Skeletally mature patients or those nearing skeletal maturity and children with high-energy injuries are treated with plate fixation. The decision to remove plates is based on surgeon preference and discussion of benefits/ risks with the patient and family. When plates are removed, a brief period of immobilization and restriction of activities is assigned to help decrease the risk of refracture.

Summary

Forearm fractures are frequent injuries in children and adolescents, which result most commonly from falls onto an outstretched hand. Careful assessment of these patients is imperative, with evaluation of the skin and soft tissues for lacerations, compartment swelling, and a complete neurovascular examination. Most pediatric forearm fractures, however, are closed injuries without associated nerve injuries or vascular compromise. The majority of these fractures are treated with closed reduction and long-arm cast immobilization under conscious sedation in the emergency department. Important complications of casting include stiffness, delayed union, and refracture.

Indications for reduction and surgical fixation include irreducible or unstable fractures that have failed an attempt at closed reduction, open fractures, a "floating elbow," vascular injuries, and fractures associated with severe soft tissue trauma or compartment syndrome. Flexible intramedullary nail fixation is the treatment of choice for most children and skeletally immature adolescents. For some fracture patterns in younger patients and for older patients near skeletal maturity, open reduction and plate fixation is another satisfactory option. Surgical treatment is generally associated with an increased number of complications, especially in children older than 10 years of age. Compartment syndrome, infections, nerve injuries, and extensor tendon injuries are the most common complications associated with surgical treatment. Careful patient selection, meticulous surgical technique, and careful postoperative care are necessary to minimize complications.

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