Open fractures in children often have a better prognosis than similar injuries in adults, and treatment may be different from that for adults.

Emergent administration of appropriate antibiotics is essential to decrease the risk of infection.

Stabilization of unstable fractures is usually beneficial, although children may require less rigidity than adults.

If viability of soft tissue is in doubt, débridement should be deferred until a later operation, as the superior healing potential of young children may produce unexpected recovery.

Associated injuries are common with open fractures in children, and serial examinations over time often uncover these injuries.

Most open fractures in children result from motor-vehicle accidents (including those in which the child is an occupant of the motor vehicle or is struck by an automobile while riding a bicycle or as a pedestrian) or falls from heights. The reported demographics and injury mechanisms have varied widely from center to center. Most investigators have reported a preponderance of boys and a predilection for the forearm and tibia. In a multicenter study of 554 open fractures in children, the sites of injury were the tibia or fibula (190 fractures; 34%), radius or ulna (178; 32%), hand or metacarpals (fifty-four; 10%), femur (thirty-seven; 6.7%), humerus (thirty-six; 6.5%), foot or metatarsals (twenty-four; 4.3%), elbow (fourteen; 2.5%), ankle (thirteen; 2.3%), and other sites (eight; 1.4%). In another study, of children presenting to one hospital, thirty-two (80%) of forty open fractures involved the forearm. In yet another study, 9% of fractures in children admitted to a tertiary pediatric trauma center were open, although we suspect that open injuries constitute a substantially smaller percentage of pediatric fractures outside of tertiary care centers.

Open fractures in children differ from open fractures in adults in many ways. Thicker and more active periosteum provides greater fracture stability and leads to more rapid and reliable fracture-healing in young children compared with that in older children and adults. Young children have a greater potential for periosteal bone formation. Healing is usually faster and more reliable in children than it is in adults with similar injuries, and children can even have reconstitution of bone in the face of bone loss. Infection rates in children with open fractures have been reported to be lower than those in adults with such fractures.

There is a gradual progression from childhood to adulthood. As children of the same chronologic age often demonstrate widely different physiologic or bone ages, it is not possible to make comprehensive recommendations based exclusively on age. Our discussion of children refers to skeletally immature patients. Patients with closed physes can often be treated according to adult algorithms.

Initial Evaluation and Management

The initial treatment of patients with open fractures requires care of the so-called trauma ABCs (airway, breathing, and circulation) and achieving control of the cervical spine. A rolled towel or pad is typically placed under the shoulders of young children to avoid neck flexion, as the proportionately large head of a child leads to neck flexion and a risk of neurologic injury when an adult board is used.

The Pediatric Advanced Life Support (PALS) and Advanced Trauma Life Support (ATLS) manuals provide helpful guidelines for the evaluation and care of children who have sustained traumatic injuries. Patients with a high-energy injury or multiple injuries should be evaluated by a trauma surgeon. Intravenous lines are started, fluid resuscitation is begun, and intravenous antibiotics are given promptly. If intravenous access is not readily obtainable, intraosseous infusion can be performed with a large bone-marrow needle with a stylet placed in the proximal part of the tibia, approximately 1 cm distal to the tibial tubercle to avoid physeal injury. Investigators studying a rabbit model noted no physeal disturbance following intraosseous infusion. Intraosseous infusion has been reported to be safe and effective in children, al-
though there have been case reports describing compartment syndrome following prolonged or rapid infusions. If intra-osseous infusion is used, care should be taken to avoid prolonged or excessively rapid infusions and to change to a standard venous access as soon as feasible.

Patients who have not had a tetanus immunization within the past five years and those whose immunization status is unknown are given a dose of tetanus toxoid. Many children do not receive their routine immunizations on time, and underimmunization was demonstrated to be prevalent in one study of patients seen at an adult emergency department. The orthopaedic surgeon cannot assume that the child is up to date with regard to tetanus immunizations or that tetanus prophylaxis has been given by other care providers. Human tetanus immune globulin provides immediate protection, but some authors have concluded that it is indicated only for patients who have never received primary immunization against tetanus, and its indications for children are unclear.

Neurologic evaluation of all of the major nerves or muscle groups is performed in both the injured and the uninjured extremities. If the patient is not able to cooperate with a full neurologic examination because of age, mentation, or trauma, he or she is observed for spontaneous motion, and any apparent deficit is noted. This may require some patience when an injured and frightened child is being examined. Small children may not answer questions regarding sensation but will often react to sensory stimuli. The results of the examination, including a notation of any portions that could not be adequately performed, are recorded. The parents also should be notified preoperatively if the patient’s neurologic status could not be fully ascertained. The vascular evaluation should include assessment of capillary refill as well as the color of the skin and digits; palpation of distal pulses; and, when the injury is severe or the pulses are questionable, assessment of distal arteries for Doppler pulses. Compartments should be palpated to ensure that they are supple. If compartments are tense or there is disproportionate pain with passive stretch of the digits, a compartment syndrome should be suspected and compartment pressures should be measured.

After wound assessment, a sterile dressing is applied. Repeat inspections involving dressing changes are minimized to avoid additional contamination or tissue trauma. Gross deformities are realigned with gentle traction to reduce the tension on soft tissues. Early splinting before the patient is taken to the operating room minimizes ongoing injury to soft tissues and decreases pain.

Classification

The modified Gustilo-Anderson system continues to be widely used for the classification of open fractures in both children and adults, although its reproducibility has been questioned. A type-I open injury is a low-energy puncture wound that measures <1 cm, with little contamination, fracture comminution, or soft-tissue injury. With type-II injuries, the skin wound is 1 to 10 cm in size, there is no extensive comminution or severe periosteal stripping, and the soft-tissue envelope is adequate for wound coverage. Type-III fractures include subtypes A, B, and C. Type IIIA indicates a heavily contaminated, segmental, or comminuted fracture with adequate soft-tissue coverage. Type IIIB includes severe soft-tissue damage that often requires coverage procedures and is typically associated with extensive periosteal stripping, exposed or comminuted bone, and heavy contamination. An open fracture is considered to be type IIIC when there are arterial injuries requiring repair, regardless of the fracture configuration, energy level of the injury, or degree of associated local soft-tissue injury.

The true extent of soft-tissue injury may be underestimated on initial examination. The stage at the time of débridement and lavage is frequently different from the initial preoperative classification, and definitive staging is best done at the time of surgery. Although intraoperative findings frequently require upgrading of the Gustilo-Anderson classification, it is important to perform the initial staging as accurately and promptly as possible, as the initial choice of antibiotics depends on accurate staging.

Infection

Factors Influencing Infection Rate

The reported rates of infection in association with type-I, II, and III open fractures in children vary widely. In a series of 554 fractures, the authors reported a 3% overall infection rate, with rates of 2% (five of 302) for type-I fractures, 2% (three of 154) for type-II fractures, and 8% (eight of ninety-eight) for type-III fractures. Hutchins et al. reported five cases of osteomyelitis in association with ten type-III open femoral fractures but no infections in association with thirty-four type-I or II open femoral fractures in the same study. The osteomyelitis rate for type-III femoral fractures reported by Hutchins et al. is sharply higher than the rates of osteomyelitis or malunion reported for type-III fractures of the tibia and other bones. This high rate may at least partly reflect the considerably higher energy that is necessary to produce a type-III femoral fracture.

In their classic article, Gustilo and Anderson reported that the infection rate associated with type-III open fractures decreased from 12% to 5% when preoperative antibiotics were given, wounds were left open, emergency débridement was performed, and no internal fixation was used. These multiple simultaneous interventions make it difficult to determine which influenced outcome and which represent confounding variables. Subsequent investigators have attempted to evaluate these factors in more detail.

Antibiotics

Prompt administration of antibiotics is clearly an important way to minimize the risk of infection associated with open fractures. In a retrospective review of 1104 open fractures in children and adults, Wilkins and Patzakis reported an infection rate of 4.7% in patients in whom antibiotics had been administered within three hours after the injury compared with 7.4% in patients who had received antibiotics more than three hours after the injury.
Patzakis and Wilkins performed a randomized prospective study of adults and children who had a total of 1104 open fracture wounds, seventy-seven of which became infected, and found that early administration of antibiotics with activities against both gram-positive and gram-negative organisms was the most important factor in reducing the infection rate. The infection rate was 2% for patients who had been given a cephalosporin, 10% for those who had been given penicillin and streptomycin, and 14% for those who had not been given antibiotics. The factors that influenced the infection rate included a failure to administer antibiotics, resistance of wound-contaminant organisms to the antibiotics, increased time from the injury to the administration of antibiotics, extent of soft-tissue damage, and open tibial fracture. Factors found to have no effect on the infection rate included the time from injury to débridement, type of wound closure, and duration of antibiotic treatment (three compared with five to ten days).

The appropriate duration of antibiotics following débridement of open fractures remains controversial. In a double-blind prospective trial of adult patients with an open fracture who received intravenous cefamandole, Dellinger et al. demonstrated no difference in infection rates between those treated for one day and those treated for five days. In most studies of open fractures in children, the authors have reported the practice of administering intravenous antibiotics for at least forty-eight hours, although this has not been conclusively demonstrated to be superior to twenty-four hours of administration.

Choice of Antibiotics

Cefazolin (100 mg/kg/day, divided into doses given every eight hours, up to a maximum dose of 2 g every eight hours) is typically administered to all patients with an open fracture. Patients with a severe type-II or III injury typically are given gentamicin (5 to 7.5 mg/kg/day divided into doses given every eight hours) in addition to cefazolin. Penicillin (150,000 units/kg/day divided into doses given every six hours, up to a maximum dose of 24 million units/day) is added to cover Clostridium species and anaerobes in patients with farm or vascular injuries. Clindamycin (15 to 40 mg/kg/day divided into doses given every six to eight hours, up to a maximum dose of 2.7 g/day) is commonly used instead of cefazolin for patients with allergies to cephalosporins or penicillin. Patzakis et al. reported that the infection rates following oral administration of ciprofloxacin were similar to the rates following intravenous administration of cefamandole and gentamicin in adult patients with a type-I or II open fracture, but the ciprofloxacin yielded inferior results in patients with a type-III fracture. However, ciprofloxacin has not been approved for use in patients under the age of eighteen years because animal data have suggested that ciprofloxacin has adverse effects on bone-healing and a possible relationship with chondropathy. Some data suggest a 2% to 3% prevalence of articular side effects in children receiving ciprofloxacin compared with a 0.1% prevalence in adults, although other studies have not demonstrated an increased risk in children. Ciprofloxacin is used extensively for children with cystic fibrosis, but routine use for children cannot be recommended at this time.

The increasing incidence of community-acquired methicillin-resistant Staphylococcus aureus infections has led some to wonder whether recommendations for initial antibiotics should be altered. We are aware of no studies demonstrating a benefit to the use of clindamycin, vancomycin, or other agents instead of cefazolin for prophylaxis for patients with an open fracture, and these alternatives do not have the same record of proven efficacy for preventing infection of open fractures. There is also concern about fostering additional bacterial resistance by the indiscriminate use of second-tier antibiotics that are best administered to treat established infections, as increasing resistance of community-acquired methicillin-resistant Staphylococcus aureus isolates to clindamycin in children has been demonstrated. Clindamycin, vancomycin, or other substitutes for cefazolin cannot be routinely recommended for first-line prophylaxis, except for patients with allergies to cephalosporins.
Local antibiotic therapy is safe, and high local antibiotic concentrations but low systemic levels are achieved. Aminoglycoside-impregnated polymethylmethacrylate beads appear to further reduce the risk of infection in type-III open tibial fractures in adults. These beads have also been successfully used in children, although additional studies may be indicated to evaluate their efficacy in populations consisting only of children. There are no standardized recommendations regarding whether antibiotic-impregnated beads should be used prophylactically during the first débridement of injuries at high risk for infection, such as type-III open femoral fractures, or only at a later débridement, when an established infection is evident. Our practice generally is to use antibiotic beads only in severe established infections.

Timing of Surgery

Traditional teaching is that open fractures must be operated on within six to eight hours after the injury. However, a literature review calls this recommendation into question. In a retrospective multicenter study of 554 open fractures in children presenting to a pediatric trauma center, an infection developed in association with 3% (twelve) of 344 fractures that had been treated with irrigation and débridement within six hours after the injury compared with 2% (four) of 210 treated seven hours or more after the injury \((p = 0.43)\). When the fractures were separated into groups according to whether they were Gustilo-Anderson type I, II, or III, there was no significant difference in the infection rate between the fractures that had been treated within six hours after the injury and those that had been treated at least seven hours after the injury in any group. The authors concluded that irrigation and débridement of open fractures in children can be performed within the first twenty-four hours after injury without increasing the risk of infection as long as intravenous antibiotics are started on presentation to the emergency department. A prior retrospective single-institution study of 104 children also demonstrated no increase in the risk of infection for surgery as the surgical delay increased from six to twenty-four hours\(^37\). In a similar study of 103 adults with an open tibial fracture, Khatod et al. reported no relationship between infection rate and surgical delay\(^38\).

We are aware of only one retrospective study of children that demonstrated an increased risk of infection when operative treatment was performed more than six hours after injury rather than less than six hours after injury\(^39\), and the authors of that study did not report the time at which antibiotics were initially administered. The study, by Kreder and Armstrong, involved open tibial fractures in children, and an infection de-
developed in two of eight cases in which the time between the injury and surgery was more than six hours compared with five (12%) of forty-two cases in which the operation was performed within six hours. We interpret these results with caution, as the numbers were so small that if one less patient had been infected in the late-treatment group, the infection rates would have been identical.

The current literature seems to indicate that delaying operative treatment of open fractures does not increase the rate of infection if antibiotics are administered early. However, such studies have not addressed the risk to the soft-tissue envelope when operative intervention is delayed. This topic remains controversial, and some surgeons strongly believe that all open fractures should undergo emergent irrigation and débridement within six hours in spite of the lack of evidence supporting this approach in the medical literature. Our practice is to operatively débride all open fractures within the first twenty-four hours and to operate emergently when a fracture is associated with neurovascular compromise, severe soft-tissue injury, or another urgent operative indication. At times, when a patient with a type-I or II open fracture without neurovascular compromise, soft tissue at risk, or a risk of compartment syndrome comes in after 10 p.m., we will wait until the next morning to provide operative treatment.

**Irrigation and Débridement**

The initial irrigation and débridement of open fractures in young children should be different from that of similar wounds in adults, largely because of the better healing potential in children. After the wound is extended and irrigated and areas of gross contamination are removed, the tourniquet (if used) is deflated to identify tissue viability. Muscle that bleeds or contracts when pinched by a forceps should be retained. In contrast to our practice with adults, we recommend retaining tissue of questionable viability in young children at the time of the initial débridement if a second débridement is planned, as we have been surprised many times by the healing in young children. Both bone ends should be visualized and cleaned, as debris may be found here even in type-I injuries.

Periosteum in young children can reconstitute bone even when there is bone loss. Devitalized bone stripped of all soft-tissue attachments usually should be removed in an adult, whereas this bone may be left in place and will usually incorporate in young children. The incised area can be gently reaproximated with simple nylon or Prolene (polypropylene) sutures, while the traumatic wound can be closed over a drain or left open. Low-grade open fractures can usually be treated adequately with a single procedure, whereas type-III and severe type-II injuries typically should undergo débridement every forty-eight to seventy-two hours until the soft tissues have stabi-
lized, the remaining tissue appears viable, and the wound is considered clean on the basis of visual inspection. For severe type-III injuries, a multidisciplinary approach including plastic surgery and, at times, a vacuum-assisted closure is beneficial.

If little additional dissection is needed, a compartment release should be done for most high-energy open fractures in which extensive soft-tissue injury can be expected, such as an open tibial fracture sustained in a motor-vehicle accident. Pain associated with a compartment syndrome may be difficult to discern from the pain associated with an open fracture in a child, so we recommend an aggressive prophylactic approach. Compartments should be palpated intraoperatively to ensure that they are supple. Pallor, paresthesias, and absent pulses are late signs of compartment syndrome.

While animal studies have demonstrated that high-pressure lavage with saline solution is more effective than low-pressure lavage for removing bacteria from contaminated wounds, especially when the irrigation is performed more than four hours after the injury\textsuperscript{41}, high-pressure irrigation has been found in vivo to have a deleterious effect on the early stages of bone-healing\textsuperscript{42}. In an animal model, low-pressure lavage with liquid soap was reported to be more effective than low-pressure irrigation with saline solution or a detergent solution for removing adherent bacteria from bone, and it preserved osteoblasts and osteoclasts better than povidone iodine, bacitracin wash, chlorhexidine solution, or detergent alone\textsuperscript{43}. Soap or detergent irrigation is more effective than saline solution or antibiotic irrigation for removing bacteria from wounds with bone injury or soft-tissue damage\textsuperscript{44-46}. Caution must be exerted when irrigation is used through a small wound as increased fluid under pressure may contribute to compartment syndrome.

Débridement Compared with Lavage for Type-I Open Fractures

Two recent studies have suggested that operative débridement may not be necessary for all type-I open fractures. Yang and Eisler reported no infections in a series of ninety-one patients, including thirteen children, in whom a type-I open fracture had been treated nonoperatively\textsuperscript{47}. In the only study of which we are aware that evaluated nonoperative treatment of open fractures in an entirely pediatric population, a deep infection was found in one (3\%) of forty children\textsuperscript{48}.

We view nonoperative management of open fractures as potentially dangerous. Because the numbers in the above studies were so small, there was a realistic potential for a type-II error (a false-negative finding) as a result of inadequate sample size. There have been rare anecdotes of children having gas gangrene or even dying after having been sent home without operative treatment for an open fracture. At an absolute minimum, patients with a type-I open fracture should receive in-hospital intravenous antibiotics and observation for forty-eight hours following irrigation of the fracture. Whether irrigation of a presumably clean type-I open fracture in an
emergency room is sufficient is open to debate, but some surgeons have described finding pieces of gravel or other contaminants during the operative débridement of even tiny, nearly pinpoint wounds that appeared to be clinically benign. In the absence of definitive studies proving the contrary, we believe that surgical irrigation and débridement are indicated for all open fractures.

**Wound Cultures**

Routine cultures before or after débridement are not indicated for patients with an open fracture. Cultures should be performed only after an infection has developed. In one study, an infection subsequently developed in twenty-four (20%) of 119 wounds for which cultures had been positive prior to débridement and nine (28%) of thirty-two for which cultures had been positive after débridement. More importantly, only 23% of the subsequent infections were caused by organisms identified by the cultures performed before débridement and 42% (eight of nineteen) were caused by organisms identified by cultures performed after débridement. Other authors have also noted little correlation between positive pre-débridement and post-débridement cultures and later infection. Thus routine cultures for patients who have no infection are more likely than not to identify an organism that is not responsible for a subsequent infection and may lead to the administration of incorrect antibiotics.

**Soft-Tissue Care**

In a study of eighty-three children with an open tibial fracture, Cullen et al. reported that a type-I or II open fracture in a child may be closed over a drain in the absence of gross contamination. Our practice is to close the surgically created extension of the wound primarily and to either leave the traumatic wound open or close it over a drain.

Early local or free-flap coverage may be indicated for large open wounds with exposed bone. Closed fractures associated with severe soft-tissue injuries may also behave like open fractures. Bumper injuries, high-energy or comminuted fractures, and fractures in patients with polytrauma can be challenging, as tenuous soft tissues may die under a cast. Delayed soft-tissue coverage of bone has been reported to increase the risk of complications, including infection and soft-tissue problems.

Open physeal fractures present special difficulties and have been excluded from many series of open fractures in children. Bae et al. reported on two open physeal fractures with severe soft-tissue loss that were successfully treated with vascularized flap coverage. New techniques, such as use of combined pedicle flaps, have been described. Severe degloving injuries about a joint may result in unrecognized physeal injury and growth arrest.

Vacuum-assisted closure has been found to be safe and effective for closure of open fractures in children, and it may obviate the need for free tissue transfers in some cases. It is thought that the vacuum-assisted closure system may improve the local wound environment and promote granulation by removing debris and soluble inflammatory mediators that may inhibit wound-healing. Use of vacuum-assisted closure in the treatment of lawnmower injuries in children led to a trend for fewer revision amputations and better post-treatment function with no treatment-related complications or adverse reactions. We use vacuum-assisted closure during the first débridement for many open fractures with large or severe soft-tissue defects that expose bone or tendon, such as ankle injuries resulting from road-dragging. We have been impressed with the results of this treatment in our practice.

Because 0.5 to 2 cm of overgrowth is generally expected following a femoral or tibial fracture in a young child, it has been stated that initial shortening of not greater than 2 cm can be accepted, although we recommend <1 cm of shortening as the upper limit, barring unusual circumstances. In young children with large soft-tissue defects, soft-tissue tension can be reduced and the defect size can be decreased by stabilizing long bones in a slightly shortened position with an external fixator or, in some cases, with flexible intramedullary rods.

The soft-tissue damage associated with an open fracture does not necessarily decompress compartments sufficiently to prevent a compartment syndrome. In adults, compartment syndrome is more commonly associated with open fractures than with closed fractures. We are not aware of similar studies of children, but our clinical experience has been that children with an open fracture are at high risk for compartment syndrome as a result of the high-energy mechanism, and appropriate clinical suspicion is warranted.

**Treatment Techniques According to Anatomic Area**

Stabilization of open fractures is essential, although depending on the fracture site, rigid fixation is not always as important in children as it is in certain settings in adults. As a general principle, the more extensive the soft-tissue damage, the greater the need for stable fixation to account for delayed fracture-healing and allow earlier mobility to prevent stiffness. A corollary is that older children whose biological capacity for healing approaches that of adults may need more rigid fixation than do young children. Fracture stabilization facilitates rehabilitation, decreases pain, and protects soft tissues. Bone-grafting is rarely necessary in young children, except those with substantial bone loss. Surviving periosteum has a remarkable ability to regenerate bone in young children, even when there is considerable bone loss.

Percutaneous Kirschner-wire fixation generally provides adequate stability for fractures of the distal part of the radius and ulna, supracondylar fractures, fractures of the distal part of the tibia, and other sites in young children. Clinical experience and animal studies have demonstrated that crossing the physis with smooth Kirschner wires of the size that is commonly used should not cause a growth disturbance.

Flexible intramedullary implants are frequently used for diaphyseal fractures of the forearm. Flexible intramedullary nails also provide good stability for most open diaphyseal and metadiaphyseal fractures of the femur and tibia that are not
severely comminuted (Figs. 3-A through 3-E). Compared with external fixation, flexible intramedullary nails allow better soft-tissue access, provide better cosmetic results, and require less patient and family care. Other anatomy-specific considerations are discussed below.

**Humeral Fractures**

Although supracondylar fractures of the humerus are common in children, there have been few reports specifically addressing open humeral fractures in children. Haasbeek and Cole reported on a series of fifteen patients with an open supracondylar, T-type, or diaphyseal humeral fracture. Seven patients presented with associated nerve injuries, and two patients had arterial injury. Two children were lost to follow-up. The long-term result was good or excellent for eleven children and fair for two. Our experience has been that the infection rate associated with open supracondylar fractures is low as a result of abundant blood supply about the elbow. We have found treatment consisting of irrigation and débridement, fracture reduction, and lateral-entry pinning to be adequate for the vast majority of open supracondylar fractures.

**Forearm Fractures**

Recent research suggests that fracture stabilization can minimize the risk of malunion or nonunion. Luhmann et al. reported on a series of sixty-five children with an open forearm fracture, including fifty-two with a type-I fracture, twelve with a type-II fracture, and one with a type-III fracture. None of thirty-eight fractures treated primarily with operative intramedullary stabilization, Kirschner wires, or plates and screws required subsequent realignment, whereas five of twenty-seven fractures treated without stabilization required additional realignment. This study supports our belief that when a child is already undergoing anesthesia for irrigation and débridement, fracture fixation adds little risk and probably provides substantial benefit by maintaining fracture reduction. Greenbaum et al. provided further support for this belief in their study of sixty-two children with an open forearm fracture. A trend for internal fixation to minimize angular deformity and reduce the need for realignment procedures was noted regardless of the fixation method (transcutaneous or intramedullary pin fixation or plates and screws), although this finding was not significant. Pins may be left protruding through the skin and then pulled out in the physician’s office in four to six weeks, when early fracture callus is seen on radiographs. Alternatively, pins may be buried under the skin and removed at a later date.

Haasbeek and Cole noted that, in a series of forty-six children with an open forearm fracture, a compartment syndrome developed in five, five presented with nerve injury, and one had an arterial injury. Ten of the forty-six children had a delayed union, malunion, nonunion, or refracture. These complications were more common in association with type-II and III open injuries. Of thirty-eight patients available for follow-up, thirty-three had a good or excellent outcome, four had a fair outcome, and one had a poor outcome.

**Femoral Fractures**

Open femoral fractures are rare but severe injuries. Hutchins et al. reported that thirty-two (4%) of 712 femoral fractures treated at a large urban pediatric trauma center from 1985 to 1996 were open. Of forty-three children with a total of forty-four open femoral fractures (twenty-five type I, nine type II, and ten type III) treated at two centers, thirteen were treated with a spica cast; twelve, with external fixation; fourteen, with locked intramedullary nailing; three, with open reduction and internal fixation; and two, with pins and a plaster cast. Complications in the patients with a type-I fracture included two cases of malalignment requiring manipulation following treatment with a spica cast, one case of osteonecrosis of the femoral head following rigid intramedullary nailing, and one case of unacceptable shortening requiring conversion from a spica cast to external fixation. One patient with a type-II fracture required an osteotomy and intramedullary nailing fol-

Fig. 3-A
An open tibial fracture sustained by a ten-year-old boy who also sustained multiple other injuries. Following irrigation and débridement, the fracture was treated with a flexible intramedullary rod that was placed proximally to avoid the tibial physis and tibial tubercle. (Figs. 3-A through 3-E reprinted, with permission, from: Skaggs DL, Flynn JM. Staying out of trouble in pediatric orthopaedics. Philadelphia: Lippincott Williams and Wilkins; 2005.)
Following a malunion after initial treatment with a spica cast. Osteomyelitis developed at the sites of five of the ten type-III fractures, and two type-III fractures treated with an external fixator went on to malunion requiring corrective osteotomy.

The authors concluded that type-I and II fractures can typically be treated with irrigation and débridement followed by age-appropriate fixation methods, whereas the optimal fixation for type-III fractures remains unresolved. Another series, of eleven open femoral fractures, demonstrated faster healing of lower-grade injuries and in younger children.

Open femoral shaft fractures in children younger than the age of six years may be treated with irrigation and débridement and a spica cast, although soft-tissue management is often a problem when a spica cast is used. Fixation with a traditional compression plate is an option for comminuted open diaphyseal fractures of the femur in children, although it is rarely the treatment of choice. Early results in small series in which a submuscular bridge plate was used for open and comminuted femoral fractures in children appear encouraging, as these procedures require less initial soft-tissue dissection than does traditional plate fixation. External fixation was widely used for open femoral fractures in children in the past. However, because of a high refracture rate, substantial scarring, and delayed unions, the present trend is for external fixation to be employed primarily for fractures that are not amenable to flexible nailing because of their location, their configuration, or soft-tissue considerations.

Few other authors have exclusively examined open femoral fractures in children, but most major series of femoral fractures in children have included both open and closed injuries. Flexible intramedullary nailing has become a preferred treatment for diaphyseal femoral fractures in children, especially those between the ages of six and twelve years. Numerous studies have demonstrated excellent results, with no nonunions or malunions, in children treated with flexible intramedullary femoral nailing. Those studies have shown dramatically earlier walking, shorter hospital stays, decreased healing times, and earlier return to school compared with those results following treatment with either external fixation or a spica cast in age-matched patient groups.

**Open Tibial Fractures**

Successful treatment of open tibial fractures in children has been achieved with a variety of means, including external fixa-

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**Figs. 3-B and 3-C** Radiographs made at four weeks after treatment show substantial callus. The flexible rod was removed in the physician’s office, and weight-bearing in the cast was encouraged.
tation, internal fixation, cast immobilization, and hybrid techniques. External fixation has been the traditional choice for open fractures with severe comminution or segmental bone loss and in medically unstable patients. External fixation has been used, with good results, for high-grade (type-II and III) tibial fractures, including those with a segmental or butterfly pattern. High rates of pin-track infection, unsightly scars, soft-tissue tethering, delayed union, and refracture make external fixators less attractive for stable fractures. In one study, rigid external fixation was associated with a 21% refracture rate at the time of frame removal. Another study demonstrated a 1.4% refracture rate in patients treated with a unilateral, more flexible fixator. The refracture rate is low if healing is noted on three cortices at the time of fixator removal. The effect of dynamization on the refracture rate is controversial. We find external fixators to be particularly helpful for maintaining a plantigrade foot while providing osseous stabilization and soft-tissue access in patients with a degloving injury about the foot and ankle (Fig. 4). Thin wire hybrid fixators are less useful for children than for adults because of the open growth plates near articular surfaces. The Ilizarov bone transport technique may be useful for the late reconstruction of injuries with large osseous defects, but it is used infrequently for acute pediatric trauma in the United States.

Intramedullary fixation with flexible titanium nails is becoming the treatment of choice for many fractures of the tibial diaphysis in children. Kubiak et al. presented a retrospective report on a series of children with a tibial fracture. Sixteen fractures (including five that were open) were treated with flexible intramedullary nailing, and fifteen (including eight that were open) were managed with external fixation. The authors found that flexible nailing resulted in faster union (mean, seven weeks) than did external fixation (mean, eighteen weeks) and yielded significantly better outcomes in terms of global function, pain, happiness, and sports activity (p < 0.01).

Cullen et al. reported on a series of eighty-three children who had an open tibial fracture. Forty fractures were fixed percutaneously with Steinmann pins and supplemental cast immobilization, thirty-two were treated with a cast only, nine were treated with external fixation, and one each was treated with internal fixation and intramedullary nailing. Of the forty fractures treated with percutaneous pinning and a cast, 23% (nine) had delayed union and 10% (four) had malunion of >10°; no malunions were reported in the patients treated with the other methods. These data suggest that, while percutane-
ous pinning of open tibial fractures in children is possible, there may be a high risk of malunion. In our practice, we prefer to use flexible intramedullary nails for this injury.

Many reports suggest that open tibial fractures have a more benign course in children under the age of eleven or twelve years, and especially in those under the age of six years\(^9\). Blasier and Barnes reported complication rates of 27% in children younger than twelve years and 69% in older children\(^8\). Court-Brown et al. noted that even thirteen to sixteen-year-old patients may have better healing than adults\(^8\). Buckley et al. identified a relationship between the time to fracture union and the severity of the soft-tissue injury, fracture configuration, segmental bone loss, and infection in children\(^7\). In a series of children with a total of ninety open tibial fractures (thirty-eight type I, thirty-five type II, and seventeen type III), Grimard et al. found ten delayed unions and seven nonunions\(^6\). Patient age and fracture type were associated with the time to union—that is, the risk of delayed union or nonunion was significantly higher in children older than the age of twelve years than in those younger than the age of six years (\(p = 0.02\)).

Robertson et al. reported on a series of open tibial fractures. Sixteen were treated with a cast alone; ten, with external fixation and a supplemental short leg cast; two, with intramedullary nailing; two, with open reduction and internal fixation; and one, with amputation\(^6\). The authors reported a significant correlation between patient age and time to union (\(p < 0.001\)). All fractures united and the fixators were removed at an average of seven weeks, with no pin-track infections. The authors concluded that, when an open tibial fracture is not associated with segmental bone deficiency or soft-tissue loss requiring major reconstruction, osseous healing can be expected within six months.

The long-term outcome of open tibial fractures in children may not be as benign as has been presumed. Reported complications have included compartment syndrome in 2% to 4% of patients, delayed union in 11% to 22%, and infection in up to 10\(^{8-9}\). Nonunion has been rare in most series of open tibial fractures, although it was reported in seven of ninety children in one study\(^8\). Limb-length discrepancy is another known complication. Overgrowth of at least 1 cm was reported following five of eighty-three open tibial fractures in one series\(^4\). In a series of ninety-two children with open tibial fractures of all types, sixty-five of which were treated with a cast, twenty-six of which were treated with external fixation, and one of which was treated with internal fixation, Hope and Cole reported a limb-length discrepancy of at least 0.5 cm in sixty patients between 1.5 and 9.7 years postoperatively\(^9\). Of seventy-four patients seen at the time of final follow-up, half reported pain at the fracture site and seventeen each had restriction of sports activity, joint stiffness, or cosmetic defects.
Open Pelvic Fractures

A study of fifteen open pelvic fractures in children treated at one institution over a twelve-year period demonstrated that, after a minimum of two years of follow-up, ten were vertically unstable. Fourteen of the fifteen fractures had been caused by an automobile-pedestrian accident, and thirteen of the fourteen had been caused by a run-over mechanism. Three of the fifteen patients died, and sepsis and infection from bowel and genitourinary sources were the most common complications. The authors recommended fracture fixation, débridement, and intravenous antibiotics for all patients, and they recommended diverting colostomies and cystostomies as indicated. External fixation can provide provisional stability while allowing abdominal access in patients with multiple injuries (Figs. 5-A and 5-B).

Special Cases

Polytrauma

Associated injuries are common in children with open fractures, especially those of the femur and tibia. Hutchins et al. reported that thirty-three of forty-three children with an open femoral fracture had associated injuries (most commonly other fractures), and Robertson et al. reported that nine of eleven children with an open femoral fracture and eighteen of thirty-two with an open tibial fracture had other major injuries. Cullen et al. reported that 58% of open tibial fractures in children treated in their center over a ten-year period were associated with other major injuries.

Motor-vehicle accidents and falls from heights are the most common mechanisms of multiple injuries in children. Up to 76% of patients with polytrauma have extremity fractures, and approximately 9% to 10% of these fractures are open. Patients with pelvic or vertebral fractures were found to have an average of five other associated injuries. In a study of 149 children who had sustained polytrauma (a total of 494 injuries), Letts et al. identified thirteen missed injuries and fifty-seven complications, most commonly due to fractures. One study suggested that treatment at a pediatric trauma center may result in lower mortality, although such centers are not available in all areas.

Polytrauma is a relative indication for the operative treatment of displaced fracture. Treatment of a patient with polytrauma with a spica cast limits access to the abdomen for serial examination, and children with a head injury who are treated with casts are at increased risk for unrecognized skin breakdown. Early stabilization of open fractures is recommended. However, although there is a relationship between delayed stabilization of a long-bone fracture, especially one of the femur, and an increased risk of acute respiratory distress syndrome, fat emboli, and deep venous thrombosis in adult patients with polytrauma, there does not appear to be a similar degree of association in children. Reporting on a series of seventy-eight children who had sustained polytrauma, Loder noted that early fracture stabilization decreased stays in the hospital and the intensive care unit, ventilator time, and overall complications. In a separate study, Loder et al. found that children with polytrauma in whom a fracture was treated more than seventy-two hours following the injury had a trend for an increased rate of immobilization-related complications, although the increase did not reach significance.

Traumatic Amputations

Traumatic amputation is the most severe form of open injury. At one Midwestern center, lawnmower injuries were reported to be responsible for 29% (sixty-nine) of 256 amputations in 235 children; farm machinery, for 24% (fifty-seven); motor-vehicle accidents, for 16% (thirty-eight); train accidents, for 9% (twenty); and other mechanisms, for the remaining 22% (fifty-one). Seasonal variation in the types of injuries has been noted, with farming injuries being more common in the summer months.

Figs. 5-A and 5-B An open pelvic fracture in the setting of high-energy polytrauma. Note that the external fixator on the pelvis allows adequate room for abdominal swelling and access for operative procedures.
spring and fall and lawnmower injuries seen more frequently in the summer months. There are also differences in the mechanisms of injury seen at different ages, with most burns occurring in younger children and boating injuries occurring primarily in adolescents.

Because of the increased wound-healing ability in children, every effort should be made to preserve all extremities of children, even those with severe type-III open fractures. There is a poor correlation between the Mangled Extremity Severity Score (MESS) and the need for amputation in a child. When amputation is required, the physis should be preserved with as much length as possible. Even a stump that initially appears very short after a traumatic amputation in a growing child may achieve substantial length by skeletal maturity if the physis is preserved.

Children have remarkable regenerative potential that allows replantation of some amputated parts that would not be salvageable in adults. Replantation following hand and upper-extremity amputations require careful postoperative cooperation of the patient and family and intensive rehabilitation. However, replanted structures in children tend to have slightly lower survival rates than those in adults because of lower selectivity by the surgeon, less favorable mechanisms of injury (including crush and avulsion mechanisms), and the increased technical challenges associated with small anatomic structures. Reimplantations also require highly specialized care that may not be available at all centers.

McClure and Shaughnessy reported that, in a series of twelve children with a farm-related amputation of an upper or lower limb, an infection developed in all six who had undergone replantation and in none of those who had not. Only two of the six replanted parts survived, with the remainder failing because of infection or vascular compromise.

Lawnmower Injuries
Power lawnmowers inflict substantial numbers of preventable fractures and amputations in children. In a series of children seen with lawnmower injuries at one center, eight of sixteen patients had sustained a traumatic amputation, fifteen of twenty nonamputation fractures involved the foot, and an average of 2.9 operative procedures were required. Five patients required free-flap transfers for soft-tissue coverage. Dormans et al. reported that, in their series of sixteen children with lawnmower injuries, all patients with a shredding-type injury had a poor result following limb salvage or ultimately required amputation. In a study of twenty-four children with lower-extremity injuries caused by a riding lawnmower, Farley et al. reported fractures in eight patients, amputations in ten, and fractures combined with amputations in six. The patients were an average of 4.7 years old at the time of injury, and they underwent an average of three irrigation and débridement procedures over a two-week hospitalization period following the injury. Sixteen children required completion of an amputation, and eleven underwent split-thickness skin-grafting of open wounds. Five patients were treated with open reduction and internal fixation of fractures, and six underwent closed reduction and cast immobilization. Five children required readmission to the hospital, and three required a third admission. At the time of a three-year follow-up, the children demonstrated a high level of athletic ability, but twelve stated that the injury affected their plans and goals for the future.

Long-Term Problems
Some patients with open fractures experience psychological problems and chronic pain. In a long-term follow-up study of eighteen children with an open tibial fracture, Levy et al. determined that missed school time averaged 4.1 months and six children had to repeat a year of school. Seven patients had a limp, five had chronic pain in spite of osseous union, and four had nightmares involving the accident. Early psychosocial intervention for severely traumatized children may be helpful to assist the patient and family in coping with the recovery process.

Overview
Open fractures in children present special challenges. The immediate administration of appropriate antibiotics on presentation is crucial to minimize the risk of infection. Formal operative débridement of all open fractures is a time-honored principle, although whether operative treatment within six hours rather than twenty-four hours influences the infection rate is controversial. Thorough débridement and irrigation of the wound with careful soft-tissue management are recommended. Open fractures in children have better healing potential than those in adults. For this reason, tissue of questionable viability should not be débrided at the first operative intervention. Unstable fractures require some form of fixation, although the fixation does not always need to be rigid, and fixation techniques should respect the physis of growing children.
References


