Overview of Wound Healing and Management

Dylan R. Childs, MD, Ananth S. Murthy, MD*

KEYWORDS
- Wound • Healing • Management • Skin • Soft tissue injuries

KEY POINTS
- Wound repair is a coordinated series of phases that have predictable cell types and microenvironments.
- Wound healing is divided into inflammatory, proliferative and maturation phases.
- The pathway of healing is determined by characteristics of the wound on presentation.
- Wounds can heal via primary, secondary or delayed primary healing.
- Debridement and negative pressure wound therapy (NPWT) are important adjuncts to treat contaminated or chronic wounds.
- Soft tissue injuries should be assessed for blood supply, hypoxia, infection, edema and foreign body contamination; and treated based on these characteristics.

PHASES OF WOUND HEALING

Wound healing is a complex, highly developed chain of events that allows people to interact with their environment. The skin is a protective organ, and it provides vital functions like temperature modulation, moisture regulation, as well as sensation, reception, and transmission. The ability to repair and regenerate is central to these functions. Wound repair is a coordinated series of phases that have predictable cell types and microenvironment preparations.

Inflammatory Phase

The initial event when a wound occurs is a platelet plug that limits bleeding and begins cytokine signaling. This event initiates the coagulation cascade and promotes amplification and recruitment of cells for the debridement of nonviable tissue. The platelets create the plug in response to exposed collagen, which then releases ADP promoting continued platelet aggregation. Aggregation is accompanied by release...
of platelet-derived growth factor (PDGF) and transforming growth factor beta (TGF-β), which is chemotactic for neutrophils in the blood.\textsuperscript{1,2}

Neutrophils are drawn to and trapped in the platelet plug in response to PDGF.\textsuperscript{1} They are the initial scavengers for debridement. They serve initially to phagocytize dead tissue and bacterial particles as well as create a wound hostile to bacteria by using reactive oxygen species. Neutrophils also provide a key proinflammatory cytokine in interleukin (IL)-1, which has dual effects as a proinflammatory cytokine and a stimulus for proliferation of keratinocytes.\textsuperscript{2} The local environment also changes; initially, there is severe vasoconstriction secondary to catecholamine release. This vasoconstriction abates shortly after and there is subsequent vasodilation in response to histamine release from circulating mast cells\textsuperscript{3,5} (Fig. 1).

As the inflammatory phase progresses, macrophages become the dominant cell type within 24 to 72 hours. Their role in the orchestration of wound healing is critical and changes as wound healing progresses.\textsuperscript{6–8} It is widely accepted that macrophages play a central role and their response is key to establishing homeostasis within the wound and downregulating the inflammatory state to avoid pathologic inflammation (Fig. 2).

**Proliferative Phase**

The proliferative phase occurs from days 4 to 21, and is representative of angiogenesis, extracellular matrix (ECM) formation, and epithelialization.\textsuperscript{9,10} Although there is considerable overlap between the phases of wound healing, the ability to transition into the next phase can determine whether a wound heals appropriately. ECM formation likely starts with platelet degranulation, because PDGF is a known promoter of proteoglycan and collagen formation. Local fibroblasts respond to PDGF by

---

**Fig. 1.** In the inflammatory phase, the fibrin clot traps the neutrophils which are the first cells in the wound. It invites the macrophage which is involved in orchestrating the process of wound healing. FGF, fibroblast growth factor; KGF, keratinocyte-derived growth factor; VEGF, vascular endothelial growth factor. (From Singer AJ, Clark RAF. Cutaneous wound healing. N Engl J Med 1999;341(10):739; with permission. Copyright © 1999 Massachusetts Medical Society.)
producing collagen as well as transforming into myofibroblasts to promote wound contraction. Fibroblasts also secrete keratinocyte-derived growth factor (KGF), which stimulates epithelialization from keratinocytes, and endothelial cells produce vascular endothelial growth factor (VEGF), and basis fibroblast growth factor (bFGF) to promote ingrowth of blood vessels. A hallmark of normal wound healing physiology is the ability to cease ongoing collagen production, with maximum deposition at approximately 21 days (Fig. 3).

**Maturation Phase**

Remodeling phase occurs from 3 weeks to 1 year after injury. It is characterized by wound contraction and collagen remodeling. Macrophages are the principal cell
type in proliferation, and fibroblasts are the principle cell type in remodeling. The hallmark process is the conversion of type III collagen to type I.\textsuperscript{12} Equilibrium between type I and type III occurs after approximately 30 days, and maximum strength occurs after roughly 42 to 60 days, hence the traditional recommendation of activity restriction after 6 weeks (see Fig. 3). Successful wound healing is contingent on adequate tissue oxygenation at the wound edges. Poor oxygenation can generally be attributed to local strangulation from excessive tension or poor delivery of oxygen to distal tissues. Local measures can be undertaken to improve tissue mobility, because excessive tension is a clinical miscalculation that inevitably fails.

**HEALING PROCESSES AND PROBLEMS WITH WOUND HEALING**

Wounds generally heal without issue and progress through one of 3 different pathways. The pathway of healing is determined by characteristics of the wound on initial presentation, and it is vital to select the appropriate method to treat the wound based on its ability to avoid hypoxia, infection, excessive edema, and foreign bodies. These factors create an environment that interrupts healing and creates a cycle of hypoxia, inflammation, necrosis, and infection, creating a chronic wound.

Surgical incisions are an example of primary healing, which is an immediate reapproximation of the skin edges, with subsequent epithelialization reconstituting the barrier within 48 to 72 hours. The key component of success with primary healing is limiting tension at the incision line, which can be accomplished by elevating deeper layers, placing progressive tension sutures to distribute the stress, with local tissue rearrangement. If there is too much tension at the suture line, breakdown occurs as a result of local tissue ischemia and necrosis.

Secondary healing is a process that uses contraction and epithelialization to restore the epithelial barrier. The wound is left open, or is in discontinuity, typically because of tension or contamination. The wound bed is kept clean and optimized for keratinocyte migration, which is generally accomplished by using hydrogels and transparent films that are waterproof and impermeable to bacteria. Once again, optimizing the wound bed to prevent hypoxia, necrosis, and infections is key to secondary healing.

Delayed primary healing is used in poorly delineated or contaminated wounds. The principle is to convert a hostile wound into a favorable one that subsequently permits surgical closure. Often adjuncts such as debridement, dressing changes, and placement of negative pressure wound therapy (NPWT) form a bridge to definitive reestablishment of an epithelial barrier. Often this method is used to treat wounds with tissue transfer; however, this can also be used as a bridge to close the wound edges.\textsuperscript{13,14} The bridging options that are available depend on the underlying structures (Fig. 4).

**Molecular Requirements for Wound Healing**

Poor oxygenation caused by inadequate delivery is a common occurrence and is often the sequela of patient-derived factors such as smoking, peripheral vascular disease, or poorly controlled diabetes. Although these diseases have a higher prevalence in the adult population, the significance of distal oxygenation must be appreciated in the pediatric population as well. Oxygen is central to many levels of wound healing and can be described as an enzymatic subcellular nutrient critical to oxidative phosphorylation and leukocyte respiratory burst, and integral for collagen synthesis.\textsuperscript{15,16}

Proper nutrition is also critical, because wound healing is an anabolic process with increased metabolic demand. Although the physiologic reserve of children is often astounding, establishing and maintaining adequate nutritional stores should be one
of the first interventions when dealing with a chronic wound. In the pediatric burn pop-
ulation, it was shown that early excision and aggressive feeding improved out-
comes. It has also been shown in animal models that the tensile strength of
wounds is significantly less than that of controls secondary to poor nutrition.

Although protein stores are central to healing, there are specific vitamin and mineral
deficiencies that can negatively affect it. The best known is vitamin C because of its
role in scurvy. It is a required cofactor for collagen cross-linking but is also implicated
in reducing oxidative stress. A deficiency of vitamin C has been associated with a
greater susceptibility to wound infection. Vitamin A has been shown to reverse the
deleterious effects of steroid use on wound healing, and has demonstrable benefit
in other conditions, such as diabetic wound care and tumors. Zinc (Zn) is an
essential cofactor in DNA and RNA synthesis, and deficiencies lead to poor wound
healing. However, the importance of Zn in wound healing was further confirmed
when the structure of matrix metalloproteinases was found to have Zn as a cofactor.
Zn benefits can be shown topically, but supplementation when levels are normal does
not augment healing.

Genetic Disorders in Wound Healing

There are heritable derangements in wound healing. These derangements are gener-
ally part of a larger spectrum of disease so effects on healing may be multifactorial.
Pseudoxanthoma elasticum is a disease that has both autosomal dominant and reces-
sive pathways. It is characterized by abnormal calcium depositions with hallmark
yellowish papules over flexure sites. There can be associated cardiac and ocular distur-
bances as well as a tendency to form keloids with delayed wound healing. Ehlers-
Danlos syndrome is characterized by hyperelastic skin and hypermobile joints. There
are 6 major types of Ehlers-Danlos and all but 1 is a heritable disorder of collagen, the
exception being a heritable disorder of tenasin. It is an autosomal dominant con-
dition often associated with mitral valve prolapse. Because of innate errors in collagen
production, wound healing is delayed and disturbed (Fig. 5). Type IV is a vascular sub-
type that has high association with arterial, bowel, and uterine rupture and often re-
results in premature death. Cutis laxa is an inborn error in elastin resulting in
severely drooping skin folds. The skin abnormalities are accompanied by cardiovas-
cular and pulmonary comorbidities, all of which result from a nonfunctioning elastase
inhibitor.
There are some inherited disorders that are contraindications for elective surgery. Werner syndrome (adult progeria) is autosomal recessive and has plaque-ridden, variably pigmented skin. Affected patients generally are short of stature with premature graying hair or baldness, trophic ulcers, and hypogonadism. The pathologic mutation is of DNA helicase, which leads to chromosomal instability and early death. The error leads to difficulty healing because of poor fibroblast function secondary to poor response to growth factors PDGF and fibroblast growth factor (FGF). Elastoderma is an exceptionally rare disease of excessive elastin fibers in the reticular dermis. It generally presents in young female patients, and the excess skin can be described as pendulous. These conditions are associated with enough morbidity that elective surgery is generally discouraged.

**Hypertrophic Scars and Keloids**

Common wound healing disorders include hypertrophic scarring and keloids. It is typically taught that if the scar remains within the border of the wound, it is a hypertrophic scar, and if it exceeds the border of the wound it is a keloid. On microscopic examination keloids possess thick eosinophilic collagen bundles, as well as a thickened epidermis and increased mesenchymal density. Often there is a difference in presenting wounds, with hypertrophic scars arising in major incisions or lacerations, whereas keloids arise from minor skin trauma. There is also an increase predilection for both in sites that are exposed to more mechanical forces, such as the sternum, shoulder, and
knee. Foreign bodies and infection also seem to be contributing factors, secondary to lengthening of a proinflammatory state within the wound\textsuperscript{33,34} (Fig. 6).

**WOUND MANAGEMENT**

*Suture Types and Postoperative Care*

Sutures can be divided into classes based on their makeup, number of strands, and permanence. When suturing in cosmetically sensitive areas, it generally advisable to use layered closures and to use a small monofilament for the most superficial layer of closure. The length of time a suture is retained can predispose to unsightly marks (railroad tracks), because the skin can epithelialize along the suture strand. Another skin closure application is the use of a cyanoacrylate. It has advantages, such as no trauma from needles; however, it alone cannot aid in alignment or support of skin edges. When suturing wounds, using a layered closure helps with final alignment and reduces tension, minimizing scar. For pediatric patients, final closure with delicate sutures, such as 6.0 rapidly absorbable suture, is often recommended for the face or cosmetically sensitive areas. A nonreactive 6.0 nonabsorbable suture can be used, but requires removal in 4 to 6 days, and removal can be difficult in the toddler population.

Postoperative care can be optimized by using a petroleum-based emollient for the first 1 to 3 weeks. After the expected fibroplasia, scar management can be addressed.

---

Fig. 6. (A) Keloids can occur in areas with no skin tension. The presence of foreign bodies, such as piercings, can be a predisposing factor. Recurrence after excision is common if no adjuvant therapy is performed. (B) Treatment commonly is preoperative, serial intralesional triamcinolone injections (usually 6 weeks apart), followed by excision. Low-dose radiation therapy (10–12 Gy) has been shown to ameliorate recurrent keloids that are resistant to corticosteroid therapy.
Often a protocol incorporating silicone-based products and scar massage aid in the aligning of collagen. It is important to convey to the patient that scar maturation can take between 6 and 12 months. Sunscreen during that time can be helpful. A scar initially is hyperemic and this indicates healing. Patience must be counseled to the patient and family because an early intervention rarely results in superior results. After a period of observation, interventions to improve scar appearance can be undertaken. Recently, Donelan and colleagues showed improvement in facial burn scarring using a pulsed dye laser. Other modalities, such as fractional CO₂ lasers, are also being studied for scar management.

Role of Debridement

The goal for any chronic wound is to convert it to an active, healing wound, which is often accomplished by debridement. Whether this is autolytic, mechanical, or enzymatic the goal is to removal all necrotic tissue. Often, adequate debridement unmasks hidden collections, revealing a much more extensive wound than was initially presumed. By removing the necrotic tissue, the wound can optimize the regenerative potential of the bordering tissue. Preservation of the adjacent viable tissue is often critical in areas where there is limited local tissue. Operatively, a limit of debriderment has often been to healthy bleeding tissue. This limit often has led to aggressive initial debridement sacrificing otherwise viable tissue. One of the adjuncts that is useful to debrideatraumatically, sparing more viable tissue, is the Versajet hydrosurgery system.

After the removal of necrotic tissue, efforts are made to transition to a granulating wound. This transition is accomplished with barrier products that protect neighboring tissue. Some commonly used barrier products are petroleum jelly, zinc oxide, and Cavilon (3M Products). These products maintain peripheral moisture while limiting superficial damage from adhesives. There is an array of topical products available. The appropriate dressing should take into account the frequency of dressing changes as well as the associated edema and moisture of the wound. If the wound is exudative, a more absorbent dressing should be selected. However, if the wound is not excessively moist, using a product that dessicates will limit keratinocyte migration. A dressing ideally provides a level of protection mimicking the epithelium’s function. However, this is a difficult function to replicate. In infected wounds, a combination of debridement and silver application is being used in many formulations and delivery. It has broad spectrum of activity against gram-negative bacteria as well as the methicillin-resistant Staphylococcus aureus (MRSA) that colonize many chronic wounds.

Negative Pressure Wound Therapy

Having a basic overview of the healing process allows various interventions to either augment or alter the healing process. One of the major advancements in wound healing has been NPWT, or vacuum-assisted closure. The principle of NPWT is its ability to create microdeformation of cells. One of its benefits is stimulation of VEGF by creating an area of relative hypoxia, as well as stimulation of other proliferative cytokines such as TGF-β and basic FGF (bFGF).

NPWT also helps to keep wounds moist, relying on a semiocclusive dressing, which prevents desiccation of wound edges. The suction apparatus also aids in the removal of fluid around the wound, limiting wound edema and maceration, which limits inflammation in chronic wounds. The dressing changes also provide a mechanical debridement.

The application of NPWT has found an increasing number of uses in pediatric surgery. Initially, NPWT was used to aid in closure of pediatric pilonidal disease and was
described as being well tolerated and permitting an earlier return to activities. Subsequent studies expanded on the anatomic regions as well as the age groups to include sternal wounds and complicated neonatal abdominal wounds, and found them to be safe and effective.

A key benefit with NPWT is that it minimizes dressing changes. Typically, NPWT dressing changes are 3 times per week as opposed to the daily or twice-daily regimens previously used. The lessened frequency and the continued improvement in the portability of the vacuum device has also allowed faster transition from the hospital setting to home with intermittent nursing visits for dressing changes. Although the up-front cost of NPWT is higher than that of standard dressing care, the overall cost is lessened, specifically when evaluated over increasing lengths of time.

### Soft Tissue Wounds to the Face

Facial soft tissue injuries are often a traumatic experience, both for the child and the caregiver. Whenever encountering these injuries, the initial focus should be on identifying and stabilizing more critical issues before addressing soft tissue injuries. Once primary and secondary surveys are complete, attention can be turned to care of soft tissue wounds. An examination assessing the function of motor and sensory nerves should be undertaken as well as documentation of the length, width, depth, and any loss of tissue or presence of contamination. Tetanus vaccine should be administered and antibiotic prophylaxis should be given, especially in bite wounds, contaminated wounds, and patients with comorbidities that predispose them to infections. Initial management should center on cleaning the wound and, if possible, early closure, because delay in closure often worsens the eventual aesthetic outcome.

The repair in superficial wounds should be undertaken within 24 hours in areas of good oxygenation and without contamination. Contaminated wounds or regions of poor blood flow should have primary closure within 6 hours if possible. With the exception of dog bites (which are generally clean), bites (cats and humans), ballistic wounds, birds, or barnyard injuries require early debridement with delayed closure to fully assess the extent of damage caused by contamination.

The scalp is a highly vascular region with anastomosis between the external and internal carotid system taking place in the loose fibrofatty region above the epicranium. This region is prone to avulsion and needs to be copiously irrigated because of the presence of emissary veins which may have connections to the dural sinus. The blood supply to the scalp often allows it to survive on a single pedicle in partial avulsion settings, but complete avulsion may require replantation. The scalp can also be extended for primary closure using galeal scoring, which involves placing horizontal incisions through the galea to expand the area of coverage. Various rotation and advancement flaps exist for scalp closure. In some cases of cranial bone exposure, the outer cortex can be burred to the diploe space followed by skin grafting, which can be used to achieve pericranial coverage. This grafting can then be treated with subsequent tissue expansion (Fig. 7).

Wounds to the ear are challenging, but most can be closed primarily. One of the most important considerations when repairing an ear wound is to prevent chondritis. If the perichondrium is intact, closure of the overlying skin is adequate. Any damaged cartilage should be carefully debrided. If the ear is totally avulsed, surgical replantation should be undertaken. Partial defects are candidates for delayed techniques of reconstruction using local flaps and cartilage grafts (Fig. 8). In cases of hematoma or avulsion, it is a general practice to place a bolster to maintain compression and prevent the formation of a hematoma. Formation of a hematoma under the perichondrium can result in anomalous cartilage healing resulting in so-called cauliflower ear.
Traumatic nasal wounds can be problematic, because the nose has a mucosal lining, along with cartilage structural units and a soft tissue envelope. The nose can be divided into several aesthetic subunits for reconstruction. This approach aids in classification and reconstruction options with local tissue flaps. Total destruction of the nose often requires an axial forehead flap based on the supratrochlear vessels (Fig. 9).

Cheek wounds can usually be primarily closed. However, the deeper structures must be assessed, specifically the parotid duct and the facial nerve. It is imperative

Fig. 7. (A) Severe dog bite to the scalp with avulsion of 50% of scalp with gross contamination. (B) After repeat debridements, galeal scoring was used to expand native scalp; burring of outer cortex, followed by incorporation of Integra. (C) Appearance after skin grafting over Integra. (D) Arrow point to tissue expanders in the scalp with recruitment of extra skin. (E) Full scalp coverage after 2 rounds of tissue expansion.

Fig. 8. (A) Dog bite with avulsion of posterior half of the ear and ear lobe. (B) Appearance after a 2-stage correction with costal cartilage graft and posteriorly based skin flap, followed by division and skin grafting to provide an auricular sulcus.
that the branches of the facial nerve are checked for function before administering any local anesthetic. The course of the facial nerve has some variability in anatomy and branching patterns, but some cardinal landmarks can be helpful (Fig. 10). The zygomatic and buccal branch can often be found at a line from the midpoint of the root of the helix to the lateral commissure of the mouth. This nerve innervates the zygomaticus major muscle and aids in smiling. The course of the parotid ducts through the cheek has often been described as a line from the tragus to the commissure. The parotid duct exits into the mouth at the level of the first molar. When duct injury is suspected, it can be cannulated with a 24-gauge angiocatheter and injected with methylene blue to assess whether a leak is present in the laceration. If present, the duct needs to be repaired over a stent.

Lip repair can involve direct repair, healing by secondary intent, rotational flaps, or microvascular replantation. Major landmarks such as the philtrum, cupid’s bow, white roll, and vermilion-mucosal junction (red line) should be carefully assessed after a laceration in the lip. Discontinuity or the loss of these landmarks requires repair, because alterations of landmarks are conspicuous at conversation distances. Small linear lacerations do not require repair because secondary healing in children

![Fig. 9](image_url)

**Fig. 9.** (A) Dog bite with consequent loss of nasal tip subunit. (B) Reconstruction with forehead flap. (C) Appearance of division and inset of the forehead. The patient can benefit from thinning of the flap at a second stage.

![Fig. 10](image_url)

**Fig. 10.** Major landmarks of the lip.
can produce excellent results. Adhesive closure without sutures has also been used with success.\textsuperscript{60} If repair of the lip is to be undertaken, accurate alignment of the landmarks is necessary.

**Dog Bites**

Dog bites are a common occurrence in the pediatric population. According to the US Centers for Disease Control and Prevention, approximately 4.5 million dog bites occur annually\textsuperscript{61} and children aged 5 to 9 years are the most at risk. This number likely understates the actual numbers because some people do not seek treatment. Two large series evaluated morbidity and interventions over a 5-year period at pediatric tertiary care centers\textsuperscript{62,63} and both found that more than half of the patients with bites had familiarity with the dog, and 1 study found that 53% were bitten by the family dog.

The location of the injury varied with age because infants and toddlers were more likely to be bitten on the face and older children were more likely to be bitten on the extremity. The studies also showed that pit bulls caused the highest percentage of bites. This finding reinforces previous studies showing that infants and young children are the most at-risk population and the most likely to incur injuries to cosmetically sensitive areas (Fig. 11).

Infection rates in dog bites vary, from 1.3% to 45%\textsuperscript{64,65}; however, the route and duration of antibiotics varied in studies. It is our practice to ensure that intravenous antibiotics are administered before washout and repair, and generally patients are sent home on an oral course of amoxicillin/clavulanate, to cover the most common bacteria in a dog’s mouth (*Pasteurella multocida*).\textsuperscript{66} A meta-analysis by Cummings\textsuperscript{67} evaluated the role of prophylactic antibiotics and showed a reduced incidence of infection with prophylactic antibiotics.

**Necrotizing Fasciitis**

Necrotizing fasciitis is a rapidly progressive and destructive infective process that is not frequently seen in the pediatric population; however, because of the speed and extent of injury, it is vital that pediatric practitioners maintain vigilance with soft tissue infections. The diagnosis is clinical and includes severe pain at the site out of

**Fig. 11.** Distribution of dog bite injuries by anatomic regions in children. Ext, extremities. (From Kaye AE, Belz JM, Kirschner RE. Pediatric dog bite injuries: a 5-year review of the experience at the Children’s Hospital of Philadelphia. Plast Reconstr Surg 2009;124(2):553; with permission.)
proportion to its appearance. The patient appears toxic, and the skin may appear mottled erythematous or even ecchymotic, and this rapidly spreads. Classically, gray dishwater drainage is described, as is subcutaneous emphysema and large bullae. In children, immune deficient diseases such as acute lymphoblastic leukemia have been implicated. One of the largest case series of pediatric necrotizing fasciitis cited malnutrition as the most common predisposing factor.68,69

Microbiology in necrotizing fasciitis is classified into 2 types. Type 1 is polymicrobial and type II is monomicrobial. Type I is often seen after abdominal surgery, rectal perforation, or a spreading infection of the perineum (Fournier gangrene). Microbes in this population are aerobic *Staphylococcus*, *Escherichia coli*, group A *Streptococcus*, and anaerobes of *Peptostreptococcus*, *Prevotella*, *Bacteroides*, and *Clostridium*. Type II is generally *Streptococcus pyogenes*. Necrotizing fasciitis is an emergency with initial management designed for resuscitation, broad-spectrum antibiotics to include clindamycin, and emergent surgical debridement to healthy bleeding tissue.

**Exposed Bone/Hardware**

Degloving injuries can occur anywhere on the body. The shearing force associated with these injuries can completely denude structures or locally separate, leaving attachments proximally and distally. The initial priority is assessment and repair of deep structures (specifically orthopedic injuries) because there is a significant risk for concomitant injuries.60 There should be a priority on maintaining any degloved skin because it can be repurposed, and viable pieces can be used as autografts. Other treatment options include tissue substitutes such as Integra and delayed skin grafting.70

The need to reconstruct the soft tissue barrier over exposed bone or hardware is critical to heal wounds and prevent infection. Godina71 recognized that the ability to transfer viable tissue over an injury was beneficial in healing. He showed that coverage of fracture within 75 hours had a lower infection rate and better time to union than coverage between 3 days and 3 months or after 3 months (1.5% and 6 month vs 17.5% and 12.3 months vs 6% and 29 months respectively).71 Pediatric free tissue transfers have been proved safe and effective.72 Some benefits of microsurgery in children include the lack of comorbid conditions and anatomy that is generally more favorable than that of their adult counterparts. Neuroplasticity is also greatly improved in children, who have better return of function than adults.72 It is important to remember that the fourth dimension of time needs to be accounted for in flap design, and although this is rarely a limiting factor it cannot be ignored.

Soft tissue coverage can be attempted for salvage of exposed hardware. The criteria needed for hardware salvage includes no hardware loosening, duration of exposure (<3 weeks), negative wound cultures, and location of the hardware with no signs of instability.73 Maintaining implants in the spine is key for stability; however, in cases of exposed extremity hardware, removal with external stabilization is still the standard of care (Fig. 12). Reconstruction after tumor resection and radiation may result in exposure and complex wounds. Because of the effects of radiation on local tissue, free tissue transfer74 is required for reconstruction. The benefits of a vascularized graft include accelerated healing and primary bone healing.75

Sternal wound infection in pediatric cardiothoracic surgery has been reported to be between 1.5% and 6.7%.76,77 Different methods to help prevent wound infections with stenotomies have been developed, such as preoperative nasal carriage screening and treatment of MRSA, preoperative chlorhexidine bathing, and optimization of pre-operative comorbidities (especially glycemic control).78 Many of the preoperative adult practices have been adopted in pediatric practice as well.79
Repair and coverage for sternal wound infections can use many adjacent flaps to provide good stable soft tissue coverage. A pectoralis flap has been used in infants for closure of sternal wound infections. Any regional transfer is generally approached in a staged fashion, with initial debridement and dressing changes for a clean wound, followed by flap closure. Rectus muscle can also be used in a vertically based fashion, but the course of the internal mammary artery to the superficial epigastric may be disrupted, so the contralateral side should be used. A regional flap that can be used with success is a pedicled omental flap. Transdiaphragmatic description has been reported in the adult literature.

Abdominal wall disorders such as omphaloceles have well-established protocols for management in infancy. Component separation (which involves separating and advancing certain layers of abdominal muscles, and lengthening their reach to achieve primary midline closure) and tissue expanders are being used to aid in closure of abdominal wall defects when classic methods are unsuccessful. Rohrich and colleagues proposed an algorithm for management of abdominal wall reconstruction, which outlined the size of the defect and an appropriate regional flap or free tissue transfer. Other groups have reported complete reconstruction of the abdominal wall in adults using the lateral circumflex system and a conjoined tensor fascia lata and anterolateral thigh flap.

In extremity reconstruction most bony defects are reconstructed using a fibula graft. Noaman performed a retrospective study in adult patients with an average defect of 8 cm of bone in the extremity. They had a 93% success rate, and, as in the spine, the benefits of vascularized bone grafting included osteogenesis at the fracture site. In the pediatric population requiring lower extremity reconstruction, 75% of patients were

---

Fig. 12. (A) Cervical spinal hardware exposure was seen after correction of scoliosis. (B) Trapezius myocutaneous flap was used to cover the hardware, for salvage and stability.
able to achieve independent ambulation, and another 20% were able to achieve assisted ambulation. Modifications can be made to the free fibular graft, such as adding cortical allografts to aid in support. Although there is the likelihood of leg length discrepancy, only 14% of patients required surgical correction (Fig. 13).

Although it may never be possible to eliminate the risk of a wound, the medical armamentarium continues to expand with methods to manage it. The expanded knowledge of cell signaling within a wound may someday allow clinicians to guide healing in a normal cascade even in abnormal conditions.

REFERENCES