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The art and science of pediatric damage control

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ABSTRACT

Damage control is a surgical strategy that has evolved and expanded considerably over the past 25 years. The approach was initially developed as a "bail out" procedure to control bleeding with severe abdominal injuries in the setting of unmitigated hemorrhagic shock. Damage control is now more broadly applied as a comprehensive management plan for the resuscitation and surgical treatment of injured patients with exhausted physiologic and metabolic reserve. This article reviews the most current concepts in damage control that are important and relevant to the practicing pediatric surgeon. It also provides evidence-based recommendations about how damage control principles can be pragmatically applied to severely injured children. This review focuses specifically on the fundamentals of damage control with respect to resuscitation and the operative treatment of children with severe abdominal, thoracic, and extremity injuries.

Introduction

Plain and simple, damage control means doing what needs to be done—and nothing more—to allow the injured patient to recover from the profound metabolic derangement that results from advanced hemorrhagic shock. Lengthy operations on a severely injured patient with advanced shock can lead to a fully repaired yet dead patient. In the early 1980s, surgeons began to recognize the value of packing and delaying definitive surgical repair until coagulation and patient temperature had returned to an acceptable level.[1] As this new surgical paradigm developed, the moniker "damage control" was borrowed from the United States Navy who defined it as "the capacity of a ship to absorb damage and maintain mission integrity".[2] In naval warfare, this strategy emphasizes rapid assessment and temporary repair of a ship's damaged hull to allow expedient return to port where repairs can be undertaken in a safer and more controlled environment.

In the early 1990s, surgeons at many American trauma centers struggled to effectively manage patients with multicavitary firearm injuries, especially patients with major vascular injuries in advanced hemorrhagic shock. The surgical damage control approach was first synthesized into a clinical concept at the University of Pennsylvania and evolved into a series of well-planned, staged phases of care.[3] The critical step in damage control is promptly recognizing patients who will benefit from having the damage control sequence implemented. In practical terms, the surgeon in damage control mode quickly accomplishes only what is necessary to keep the patient alive and delays definitive repairs and anatomic reconstruction until the patient has been stabilized.

The objective of this review is to illustrate fundamental damage control principles in a practical way that can be applied by pediatric surgeons who do not exclusively care for trauma patients. This review describes the most salient evidence-based concepts in damage control and extrapolate from methods used in adults that are pertinent to injured children.

General considerations

Surgeons who care for injured children should approach every patient with potentially significant injuries from a damage control mindset. Simply put, this means having a low threshold for application of the principles of damage control resuscitation and rapid surgical treatment of traumatic injuries in children with evidence of advanced hemorrhagic shock. Ideally, the damage control approach starts in the field with the [C]ABC paradigm for priorities of treatment—Catastrophic bleeding, Airway, Bleeding, Circulation. About one-third of trauma-related deaths following hospital admission can be attributed to major uncontrolled bleeding.[4] These deaths are potentially preventable with prompt hemorrhage control and resuscitation that begins with the avoidance of crystalloid administration, and early infusion of blood products in a balanced ratio [i.e., 1:1:1 for units of plasma to platelets to packed red blood cells (pRBCs) in adult patients].[4,5]

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Surgeons must recognize early and attempt to mitigate the "triangle of death". This lethal triad is a viscous cycle of three separate, but closely interrelated clinical elements (acidosis, hypothermia, and coagulopathy) that will become irreversible if not identified early and treated aggressively.[6] Pediatric patients have increased surface area to body mass ratio, thinner skin, and a relative paucity of subcutaneous fat, which makes them more susceptible to the effects of a cold environment. Furthermore, blood loss secondary to trauma is difficult to estimate in adults or pediatric patients. Therefore, a pediatric surgeon must recognize mechanisms with a potential to produce significant hemorrhage that could represent half of an injured child's blood volume (i.e., 40 mL/kg).

The three widely accepted phases of damage control are:

1) Limited operation to control bleeding and contamination, exploration, and rapid temporary closure.
2) Resuscitation in the pediatric intensive care unit with rewarming, transfusion, and hemodynamic support.
3) Reoperation for definitive repair of injuries and wound closure.

Variation in surgeon utilization of damage control surgery across North American trauma centers has been observed, and it is likely driven by surgeon uncertainty about when a damage control approach is indicated.[7] While there are not good data from pediatric trauma patients to guide practice, consensus-driven practice guidelines from adult civilian trauma patients exist.[8,9] Recommendation for the use of a damage control surgery from these studies include a preoperative core body temperature $<34°C$, arterial pH $<$ 7.2, INR/PT $>$ 1.5 times normal, clinically observed coagulopathy, and blood loss of greater than half the patient's blood volume (i.e., 40 mL/kg).

Damage control resuscitation

Hemorrhage poses the most significant threat to injured patients presenting to trauma centers for evaluation and definitive care. The most recent data suggest that most early deaths in trauma patients occur within 2–3 h of hospital arrival, and are the result of ongoing hemorrhage and coagulopathy.[10,11] Damage control resuscitation has been defined as early hemorrhage control with administration of blood products in a balanced ratio (1 plasma:1 platelets:1 pRBCs), correction of coagulopathy, and avoidance of crystalloid fluids.[5] A recent randomized trial demonstrated that early administration of blood products in a 1:1:1 transfusion ratio optimally attains hemostasis and lowers mortality.[12] However, it is important to note that a consensus is lacking in the pediatric surgery community regarding the ideal transfusion ratio with much of the recommendations being derived from adult trauma patients.[13,14]

For this reason, massive transfusion protocols (MTP) should play a key role in the early treatment of injured children and adults in hemorrhagic shock while life-threatening injuries are identified and surgical bleeding is controlled. Massive transfusion protocols are mandated by the American College of Surgeons for trauma center verification because they create a process whereby blood loss can be replaced with something close to whole blood while the evaluation and treatment of injured patients occurs. It is critically important that institutions caring for injured children have a MTP that can reliably be activated, and that they evaluate processes of care each time the MTP is used to refine their protocol and performance with it (Table 1).

Massive transfusion has been classically defined as the administration of a large volume of whole blood or packed red blood cells over a given time period. Two more recent and specific definitions for massive transfusion in adult patients include (1) transfusion of greater than or equal to 10 units of pRBCs (approximately one total blood volume of an adult) within 24 h of arrival and (2) transfusion of greater than 4 units of pRBCs within 1 h with anticipation of an ongoing transfusion requirement. For pediatric patients, the following definitions for situations requiring massive transfusion have been described: (1) transfusion of greater than 100% of the child's total blood volume over a 24-h period; (2) transfusion support to replace ongoing hemorrhage of greater than 10% of the patient's total blood volume per minute; and/or (3) replacement of greater than 50% of the child's total blood volume by blood products in 3 h or less.[13] This definition was recently corroborated by a study of combat-injured pediatric trauma patients from the Department of Defense Trauma Registry, which identified a threshold of 40 mL/kg (i.e., half a blood volume) of all blood products given at any time within 24 h of injury reliably identifies children at high risk for early and in-hospital death.[15] Therefore, children presenting with persistent hemodynamic instability, active bleeding requiring treatment in the operating room or interventional radiology suite, transfusion of pRBCs in the trauma bay, and surgeon suspicion of major hemorrhage should prompt activation of the institutions MTP with early use of blood products over crystalloid or colloid solutions (Tables 2–4).

The utility of pharmacologic adjuncts (i.e., tranexamic acid, recombinant factor VIIa, and prothrombin complex concentrate) and hemostasis assays [i.e., thromboelastography (TEG) and rotational thromboelastography (ROTEM)] in pediatric trauma patients have the potential to guide resuscitative efforts in the future. Two recent studies have shown a potential survival advantage with tranexamic acid administration in pediatric trauma patients and found decreased mortality associated with its use.[16,17] However, the utility of these adjuncts in the care of civilian pediatric trauma patients warrants further investigation.

Abdominal damage control

Injured children with indications for trauma laparotomy and evidence of advanced hemorrhagic shock should have this procedure accomplished quickly with three primary objectives: control bleeding, control contamination, and temporary abdominal closure. The operating room should be warm and a wide surgical prep should be established incorporating the chest, abdomen, and thighs to facilitate saphenous vein harvest, ostomy creation, drain placement, and/or temporary abdominal closure if required. A large incision (xiphoid to symphysis pubis) to facilitate optimal

Table 1
Indications for pediatric damage control surgery. (Adapted with permission from Roberts et al.[7])

1. Patient requiring large-volume resuscitation with blood products
2. Profound shock—hypothermia (temperature $<34°C$), acidosis (pH $<$ 7.2), and/or coagulopathy (INR/PT $>$ 1.5 $\times$ normal)
3. Complex injury mechanism requiring resection and/or reconstruction - for example,
a. Expanding/difficult to access pelvic hematoma
b. Juxtahepatic venous injury
c. Disruption of the pancreaticoduodenal complex