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DAMAGE CONTROL BEYOND THE ABDOMEN (E DEGIANNIS, SECTION EDITOR)

Thoracic Damage Control Surgery

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Abstract

Purpose of Review An overview of the practice of damage control surgery in the thoracic trauma patient with emphasis on physiological resuscitation and specific management principles of damage to different organs in the chest.

Recent Findings The advance of endovascular stents use for injuries of the large thoracic vessels can greatly assist in avoiding open surgery with major bleeding in a patient in physiological extremis. Extracorporeal membrane oxygenation (ECMO) can be used in those patients where conventional measures of resuscitation and oxygenation fail as an adjunct to restore normal physiology.

Summary Thoracic damage control surgery can be employed successfully if the physiology of the patient is paramount during resuscitation chasing the specific goals of reversing the lethal triad of acidosis, coagulopathy, and hypothermia. Abbreviated surgical techniques which mainly achieve hemostasis and control air leaks needs to be carefully employed in the thoracic cavity where packing of organs for hemostasis can greatly compromise cardiorespiratory reserve.

Keywords Damage control surgery · Thoracic trauma

Introduction

Initial reports for damage control surgery were described in the clinical setting of abdominal trauma focusing on the control of ongoing bleeding and avoiding further contamination of the abdominal cavity while allowing physiological reserve to normalize by correcting the lethal triad of hypothermia, coagulopathy, and metabolic acidosis [1, 2]. Conventionally extensive procedures were abbreviated in a technically faster and simpler fashion in order to concentrate on rewarming the patient and correcting coagulopathy and acidosis. Reversal of this lethal triad is usually established by ongoing resuscitation from the emergency room, through to the theater, and continuing into the intensive care unit. Once the patient was warm, with a normal pH, good hemostasis and adequate coagulation, a return to theater ensured more definitive surgical procedures can be completed in a physiologically more resilient patient.

In thoracic trauma patients of physiological extremis, the same basic principles of damage control surgery can be applied (control ongoing bleeding and avoid contamination of the thoracic cavity) with the basic difference that vital thoracic organs be repaired adequately at initial surgery to maintain life supporting physiology and ensuring that packing for hemostasis does not compromise cardiorespiratory physiology. Adequate evidence exist that the abbreviated thoracotomy of damage control reduce mortality [3]. The life-saving emergency department thoracotomy essentially depicts damage control in its purest form giving access to advanced resuscitation techniques in the physiological extremis patient like open cardiac massage, an endotracheal tube into an airway injury to establish a safe airway or control of major bleeding.

Damage Control Resuscitation in Thoracic Trauma

The lethal triad of hypothermia, acidosis, and coagulopathy in the trauma patient majorly affects survival in the trauma patient [4]. The whole concept of damage control surgery balances on the paradigm shift that initial life-saving procedures should be performed but abbreviated, allowing time for physiological reserves to be re-established by careful metabolic guided resuscitation to improve hemostasis in order to definitively

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manage injuries at a later stage. When the trauma patient has replete coagulation and other physiological reserves, definitive surgery can be performed (usually 36–48 h later). Most preventable trauma deaths are due to uncontrolled hemorrhage and therefor resuscitation strategies should include body rewarming, restrictive fluid administration, permissive hypotension, balanced blood product administration, and the implementation of massive transfusion protocols with the major aim of correcting coagulopathy in the exsanguinating trauma patient.

Hypothermia should be addressed by passive external rewarming (keep the environmental temperature high in the emergency room and theater, remove wet clothing, and swop to warming blankets), active external warming (forced-air warming mattresses and blankets) as well as active internal warming of the core (humidified and heated ventilation gasses, warm intravenous fluids and blood products, and warm irrigation fluid during damage control surgery of the chest).

Acidosis should be actively prevented and treated aggressively when present. There is no current evidence for intravenous bicarbonate or tris-hydroxymethyl aminomethane (THAM) administration in trauma patients. A superior strategy would be to maintain or restore adequate tissue perfusion by adequate perfusion pressure established by appropriate fluid administration and judicious use of inotropes [5, 6].

Active hemostatic resuscitation should be the ongoing goal during damage control—give blood products early and in a higher ratio with packed cells. The benefit of transfusing blood products (fresh frozen plasma and platelets) early while giving packed red blood cells was confirmed in a multicenter trial, especially in the patient population that receive more than 10 units of packed red blood cells [7].

The use of extracorporeal membrane oxygenation (ECMO) in the thoracic trauma patient where damage control principles are followed can be life-saving. Physiology correcting adjuncts like ECMO, need to be considered in those patients where active physiological resuscitation and attempts to reverse the lethal triad, does not translate in clinical progress and packing of the thoracic cavity compromise cardiorespiratory reserve. The ECMO system can be used with high blood flows and no heparinization of the circuit plus the additional advantage of an inline blood heating system until clinical hemostasis is adequate. This strategy is yielding promising results in some desperate thoracic damage control situations [8].

Incisions

When opening the chest in damage control surgery, quick access to the thoracic vital organs should be paramount. The most utilized incision is the left anterior or anterolateral thoracotomy via the 4th intercostal space with easy access to the pericardium and its content while remaining a quick, relative bloodless entry. If the right side of the heart proves difficult to manage from this left sided incision or the right pulmonary hilum needs to be reached, the incision can be extended transversely over the sternum with a transverse division of the sternum and even further into the corresponding right intercostal space to evolve into a clamshell incision. Median sternotomy (with cervical extension if needed) provides excellent access to the heart and ascending aorta with aortic arch vessels. Posterolateral thoracotomy addresses the pulmonary hilum, descending aorta (if left sided), and esophagus well [9].

Damage Control Techniques in Various Thoracic Anatomic Injury Sites

Lung Injury

Several damage control techniques have been described for the management of severe lung trauma. The practice of pneumonorraphy, pulmonary tractotomy, twisting or clamping the pulmonary hilum for bleeding control, en-masse stapling of the hilar structures, and standard resections in the form of wedge resection, lobectomy, or pneumonectomy have all been used successfully in thoracic trauma [10].

The principle of halting ongoing bleeding as soon as possible, not performing prolonged or demanding technical procedures in patients in physiological extremis as well as limiting spilling of pulmonary secretions from the endobronchial surface to the thoracic cavity, should be maintained at all times.

Adequate hemostasis is a prerequisite for pneumorraphy. In this technique, the entry and exit wounds of lung injuries are oversewn. As the result of ongoing bleeding in the lung parenchyma which is hidden by the pneumorraphy, bleeding can expand into the lung tissue with spilling of bloody secretions endobronchially and possibly soiling the contralateral lung. It is therefor imperative to ensure adequate hemostasis of the underlying lung parenchyma before pneumorraphy is performed and a tractotomy might be required definitively to treat this bleeding [11].

The very useful technique of tractotomy assists in managing through and through injuries of the lung which does not involve the hilar blood vessels. By placing a linear stapler through the injury tract, stapling the tract open, lung tissue is laid bare, with ease of access to bleeding parenchyma or areas with air leaks. These can be managed efficiently by the usual technique of a first layer of horizontal mattress suturing (large needle, preferable vicryl, or polypropylene suture) and a second layer of a running oversewing suture. A tractotomy preserve lung tissue in general by avoiding unnecessary resections. If no stapling device is available, both edges of the tract can be clamped with a Roberts clamp, the tissue divided in between and the tract managed as described above (the poor

man's tractotomy). Special care to avoid air leaks needs to be used in this instance.

The well-established trauma surgery technique to an actively bleeding lung with or without a massive air leak is the hilar twist (the inferior pulmonary ligament of that lung is mobilized and the lung twisted or torted around its own hilum) or simply apply a large vascular clamp across the pulmonary hilum for temporary control. Lobectomy or pneumonectomy in the physiologically depleted trauma patient can be postponed in this manner addressing the clinical demands of physiological resuscitation first before returning to theatre for a definitive resection [12].

Cardiac Injury

The classic emergency room thoracotomy for the control of bleeding or the relief of tamponade due to cardiac injury epitomizes the essentials of damage control surgery: it provides an aggressive, fast technique with rapid control of the bleeding cardiac injury which will deplete the patients physiology completely if not addressed immediately, sometimes in a temporary control fashion with more definitive control later in theatre. The first aim should be to relieve cardiac tamponade immediately and hereby avoid diastolic restriction. Many authors describe the technique of inserting a Foley's catheter in the injury site of the heart with balloon inflation and hereby attempt to gain control of the bleeding in order to prepare for suturing of the defect. Through experience, it is certain that this maneuver wastes more time than a simple finger of the surgeon or assistant on the bleeding cardiac injury with a second pair of hands suturing the defect. It is also useful to remember the quick and effective application of skin staples in dealing with a cardiac injury. If needed, the completed skin staple line can afterwards be supported with a pledgeted U-suture for complete hemostasis. Atrial injuries often provide more frail cardiac tissue to suture while ventricular injuries prove to supply more robust myocardium to work with during suturing. Be aware of this and treat atrial tissue with respect, especially in elderly patients.

It is imperative that injuries close to coronary arteries be managed with sutures wide and deep (beneath the vessel) from the coronary arteries. These injuries need to be treated expeditiously with proximal coronary artery injuries grafted on cardiopulmonary bypass and distal coronary artery injuries ligated. In special circumstances, a cardiac surgeon with the expertise to perform "off-pump" coronary artery bypass grafting may be available and extremely useful in the setting of the trauma patient with the support of intra-coronary shunts to maintain distal coronary perfusion and the utilization of readily available grafts in the form of a saphenous vein [13].

Remember to check for injuries to the posterior surface of the heart by elevating the heart with a hand lined with a Ratex swab. This elevation should be prompt and brief, after warning the anesthetist (in order to optimize hemodynamics and volume status prior to the elevation of the heart) and putting the heart back in the pericardial sack as soon as possible in order to give it some time to recover hemodynamically before embarking on any further attempts to suture the posterior surface if needed. During all suturing of the heart, Teflon or pericardial pledgets should be used in order to avoid sutures tearing through the frail myocardium [14].

During the management of some difficult to control cardiac injuries, one might need a "more bloodless" field. This can be provided in extreme conditions by inflow occlusion using an atraumatic vascular clamp applied to the superior and inferior vena cava (SVC and IVC) separately, avoiding the sino-atrial node (SA-node) area in the case of the SVC. Alternatively, a careful and attentive hand with a swab on the right atrium can compress the right atrium with volume loss to the heart and thereby less bleeding from the cardiac injury. These maneuvers should only be incorporated in desperate situations as it may be almost impossible for a struggling, injured heart to recover from these physiologically challenged situations with accompanying hypovolemia [15]. Dangerous techniques to control bleeding like cross clamping of the ascending or descending aorta should be avoided as far as possible in view of the irreversible cardiac damage associated with left ventricular distension in the case of volume overload due to outflow obstruction by a cross clamp.

Tracheobronchial Injury

Fortunately, tracheobronchial injuries are relatively uncommon with most blunt trauma cases being associated with high-energy-impact motor-vehicle accidents while penetrating trauma are still responsible for most injuries involving the airway. Research showed that 76% occurs within 2 cm of the main carina and 43% within 2 cm of the right main bronchus while the most common signs and symptoms stay dysphonia, subcutaneous emphysema, pneumothorax with a massive air leak, and hemoptysis [16].

Airway management should take preference in any patient, while major injuries to the trachea or bronchi can prove difficult to manage definitively in the trauma patient. The incorporation of flexible bronchoscopy in the management of these patients can be life-saving. In the first place, secure the airway—this may mean a cuffed endotracheal tube through the injury site in the airway often preferentially down either the right or left main bronchi to isolate ventilation to the non-injured lung and exclude an actively bleeding lung from the trachea-bronchial tree. This maneuver obviously establish the opportunity to oxygenate and ventilate the patient but also prevent spilling of endobronchial secretions into the thoracic cavity.

The best approach to the proximal two thirds of the trachea is via a lower cervical incision but the lower third of the trachea, the area surrounding the carina, and the proximal aspects

of both right and left main bronchi should be managed via a right thoracotomy. Simple, clean lacerations can be primarily repaired with absorbable suture material like polidioxanone (PDS^{R}) or vicryl. Interrupted sutures should be used for the cartilaginous part of the airway and running or continuous sutures for the membranous trachea keeping knots on the external surface. Complex lacerations with large defects in the wall of the tracheobronchial tree may require tracheal resection or sleeve reconstructions of the carina and main bronchi or in the case of injuries distal to the hilum, resection in the form of lobectomy or pneumonectomy. In this instance the distal airway should be managed with a cuffed (preferably armored) endotracheal tube as part of damage control principles and the physiology of the patient judged for fitness for major surgery with a possible decision to return to theater once more stable as long as ventilation is safely established (in an adequate fashion to re-establish adequate gas exchange as well as contain the spilling of endobronchial secretions to the minimum). For major destructive injuries of the trachea, the option of a silicone T-tube as a safe temporizing measure should be kept in mind. This maneuver gives rapid control of the airway, is easy to perform, a small endotracheal tube can be safely placed through it with subsequent ventilation and can be left in place for extended periods with definitive planned repair weeks later if necessary [17].

Esophageal Injury

The majority of esophageal injuries are due to penetrating trauma with blunt injury being extremely rare. The management of esophageal injuries demonstrates the principles of damage control surgery with primary temporary control and avoidance of contamination of the body cavity, very well. Furthermore, the management of injuries to the esophagus depends on time from injury to presentation. If esophageal injury is diagnosed in the first 24 hours and wound edges appears fresh and not necrotic, a direct primary repair can be performed, supported with a nasogastric tube and free drainage as well as a pleural drain well positioned next to the area of repair. If esophageal injuries are discovered more than 24 hours later, necrotic wound edges should be debrided, the area of esophageal injury drained with a T-tube if possible, and wide drainage and irrigation of the peri-esophageal planes performed with drains left in these spaces. Extensive and septic injuries with associated mediastinitis should be treated with a diversion procedure like cervical esophagostomy and an accompanying feeding gastrostomy. The incidence of mediastinitis (with a 50% associated mortality) is high with esophageal injury and especially if presenting late. In the case of any injury of the mediastinum, a thought should be spared for possible esophageal injury and if suspected, all attempts should be made to diagnose and manage this early [18].

Intrathoracic Vascular Injury

Goncalves and Saad very accurately describe the 3 clinical scenarios encountered in damage control surgery for thoracic vascular injury: active, externalized bleeding from an open wound, active bleeding into a compartment of the thorax (classically the pleural space or any of the anterior, middle, or posterior mediastinal compartments), or contained bleeding supported by evidence of a mediastinal or extrapleural hematoma [18]. Externalized bleeding can be temporized by a Foley's catheter with inflated balloon into the skin defect with an additional surrounding hemostatic purse string suture if needed. A further option for temporary hemostasis is an endovascular Fogarty catheter placed intraluminally in the vascular structure with inflation of the balloon distally [19]. Expeditious further management of thoracic vascular injuries with external bleeding is all about planning proximal and distal control of the injured vessel. In case where an anterior emergency room thoracotomy has already been performed, proximal control is relatively simple. Distal control depends on the site of injury and might require a sternotomy extended to a cervical incision to control head and neck vessels or a more lateral extension of the anterior thoracotomy to reach the descending aorta. "Trap door" exposure with mobilization of the clavicle may be needed but carries significant morbidity [20].

The best outcome would be to establish primary repair of intrathoracic vessels but if physiology of the patient does not allow this, temporary shunts (like an Argyle carotid shunt) can be placed intravascularly with definitive repair at a later stage once the patient has physiologically stabilized. If vasculature is destroyed to an extent where primary repair cannot be achieved, a Dacron or woven polytetrafluoroethylene (PTFE) graft should be placed for vessels larger than 5 mm.

It is important to remember that most intrathoracic veins (with the exception of the vena cava) as well as the subclavian arteries can be safely ligated—this may be life-saving in the damage control scenario. Extended period clamping of the ascending or descending thoracic aorta is usually uniformly fatal.

Should a large mediastinal hematoma be due to a large vessel bleed, one could opt for conservative management of the vascular injury during the damage control period, control the blood pressure well in order to avoid sudden systolic pressure increases when physiology has been normalized and subject the patient, then to fluoroscopic guided endovascular stenting of the descending aorta or large aortic arch vessels. A thoracotomy to address the source of bleeding by opening such a mediastinal hematoma in the acute setting could lead to massive bleeding which would be poorly tolerate by a physiologically frail patient.

Thoracic Wall Injuries

Extensive injuries of the muscular and vascular thoracic wall can result in major morbidity and mortality especially in the setting of a physiologically depleted trauma patient threatened by the lethal triad of coagulopathy, hypothermia, and acidosis. Prompt, adequate hemostasis is key and attention to intercostal and internal thoracic ("mammary") arteries is imperative—these arteries can be in spasm at the time of surgery but later when the patient is warmed up with improved blood pressure and cardiac output, it can dilate and cause significant blood loss. Another significant source of bleeding can be from the parietal pleural surface—this needs to be managed carefully and the use of an Argon plasma coagulation system in combination with a cautery device can provide excellent results in these raw surfaces.

The use of selective packing of the thoracic wall has been employed with mixed results—it provides reasonable hemostasis but can impair cardiorespiratory physiology by preventing lung expansion or cardiac relaxation in diastole. The paravertebral space, apex of the lung, and the area between the diaphragm and the lung in the diaphragmatic recesses are renowned difficult areas for chest wall hemostasis. In this instance or any situation with difficulty in controlling bleeding from the thoracic cage, selective packing can be utilised for uncontrollable thoracic wall bleeding as described by Perez-Alonso et al. where gauze packs are placed on active bleeding sites and hemostasis achieved by using intra- and extra-thoracic Ventrofil (®) devices with coated wired stitches tightly fixed to the skin in a sandwich-like fashion between the skin and the pleura. This technique achieves good hemostasis while preserving cardiorespiratory function [21].

Closure of Thoracic Incisions

In the situation of damage control surgery of the chest, closure of different incisions needs to be carefully managed.

After cardiac injury and massive transfusions, the heart can be edematous with a delicate point of function on the Frank Starling curve especially in diastole when external compression of the sternum on such an edematous, traumatized heart can lead to decreased or no cardiac output. In this situation, the sternum can be left open and only the skin closed with the "Bogota bag" technique where a sterilized Saline bag is cut open into an elliptical shape and fashioned as a cover, sewn into position, for extra cover of the gaping skin wound of the chest. In this situation, it is imperative that adequate surgical hemostasis of the content of the pericardial sac is obtained, as continuous bleeding is often a problem without the opposition of the sternum which is responsible for the hemostatic closed cavity effect of the mediastinum. The patient should be kept intubated, ventilated, and sedated well (preferably with muscle relaxation) as coughing with an open sternum can slice or injure the vulnerable right ventricle.

For closure of thoracotomy wounds in this setting, it has been proposed in the past that towel clips be used for rapid closure as described in the abdomen. Towel clip closure only prevents heat loss but does very little to enforce hemostasis which can be a major problem from the vascular chest wall. It is far more hemostatic (and probably faster) to run a large needle interlocking en-masse closure suture technique, which incorporate the thoracic cage, muscle and skin in one setting for thoracotomies, especially in the posterolateral thoracotomy incision where different muscle layers provide space for ongoing occult bleeding post-operatively in the coagulopathic patient of physiological extremis. Far less muscle bulk is implicated in the anterior or anterolateral thoracotomy access, but the same principle applies [22, 23].

Conclusion

The successful implementation of damage control surgical strategies of the thoracic trauma patient requires a combination of skilled, quick surgical access to appropriately address different injuries in the chest as effectively as possible while ongoing physiological resuscitation aims at reversing the lethal triad of coagulopathy, acidosis, and hypothermia. These practices can be employed successfully in this complex patient group provided a clear view of the overall metabolic and hemostatic status of the patient is used to guide abbreviated versus definitive repair.

Compliance with Ethical Standards

Conflict of Interest The authors declare no conflicts of interest relevant to this manuscript.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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