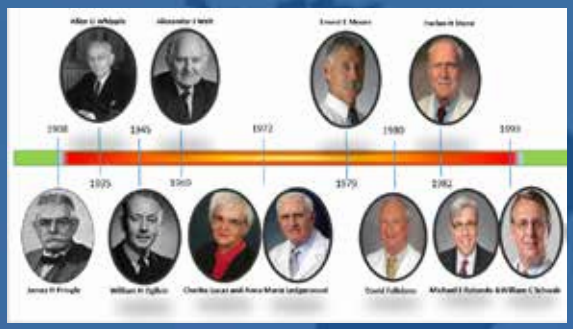
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Milestones and Key Figures in the Development of Damage Control Surgery

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REVIEW

Damage Control Surgery: An Update

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Abstract

The historical evolution of damage control surgery (DCS) represents a pivotal journey within trauma management, transitioning from foundational principles to contemporary advanced practices. Established through the identification of the lethal triad—hypothermia, acidosis, and coagulopathy—DCS addresses the complex needs of severely injured patients in both civilian and military contexts. This review emphasizes key contributions in the field, including traditional DCS with open abdomen, to adjunct innovative techniques used together with DCS today. Many surgical clinical figures have shaped the practice of DCS. Among them are Pringle's temporary occlusion techniques for diagnosing and controlling hepatic hemorrhage, A. O. Whipple's staged laparotomy, and Ogilvie's stomas in colorectal trauma. Others questioned DCS such as Madding and Kennedy, whose observations during World War II raised concerns regarding liver packing practices due to the risks of severe complications like sepsis. Yet, Lucas and Ledgerwood demonstrated the necessity of rapid hemostatic control for better patient outcomes, challenging these concerns significantly. The effectiveness of temporary laparotomy pad tamponade was highlighted in studies by Stones, Feliciano, Ivatury and many others showing high survival rates for patients with liver injuries. Stone's landmark study contrasted survival rates of patients treated with abdominal packing to historical controls, leading to rapid acceptance of staged laparotomy strategies. Finally, Rotondo and Bill Schwab were instrumental in formalizing DCS concepts for exsanguinating penetrating abdominal injuries, advocating for a staged approach that significantly improved survival rates. Through these contributions, this paper illustrates the progression and refinement of trauma surgery aimed at enhancing survival outcomes during critical injuries.

Keywords: Damage Control Surgery (DCS); Trauma; Hemodynamic Instability; Direct Peritoneal Resuscitation (DPR); Damage Control Resuscitation (DCR); Surgical Interventions; Multidisciplinary Approach; Trauma Management; Navy Damage control concept

HISTORICAL NOTES ON THE EVOLUTION OF DAM- AGE CONTROL

The evolution of damage control surgery (DCS) reflects a cyclical journey of recognition and acceptance within trauma management, initially conceptualized through the acknowledgment of the lethal triad of hypothermia, acidosis, and coagulopathy (Figure 1).

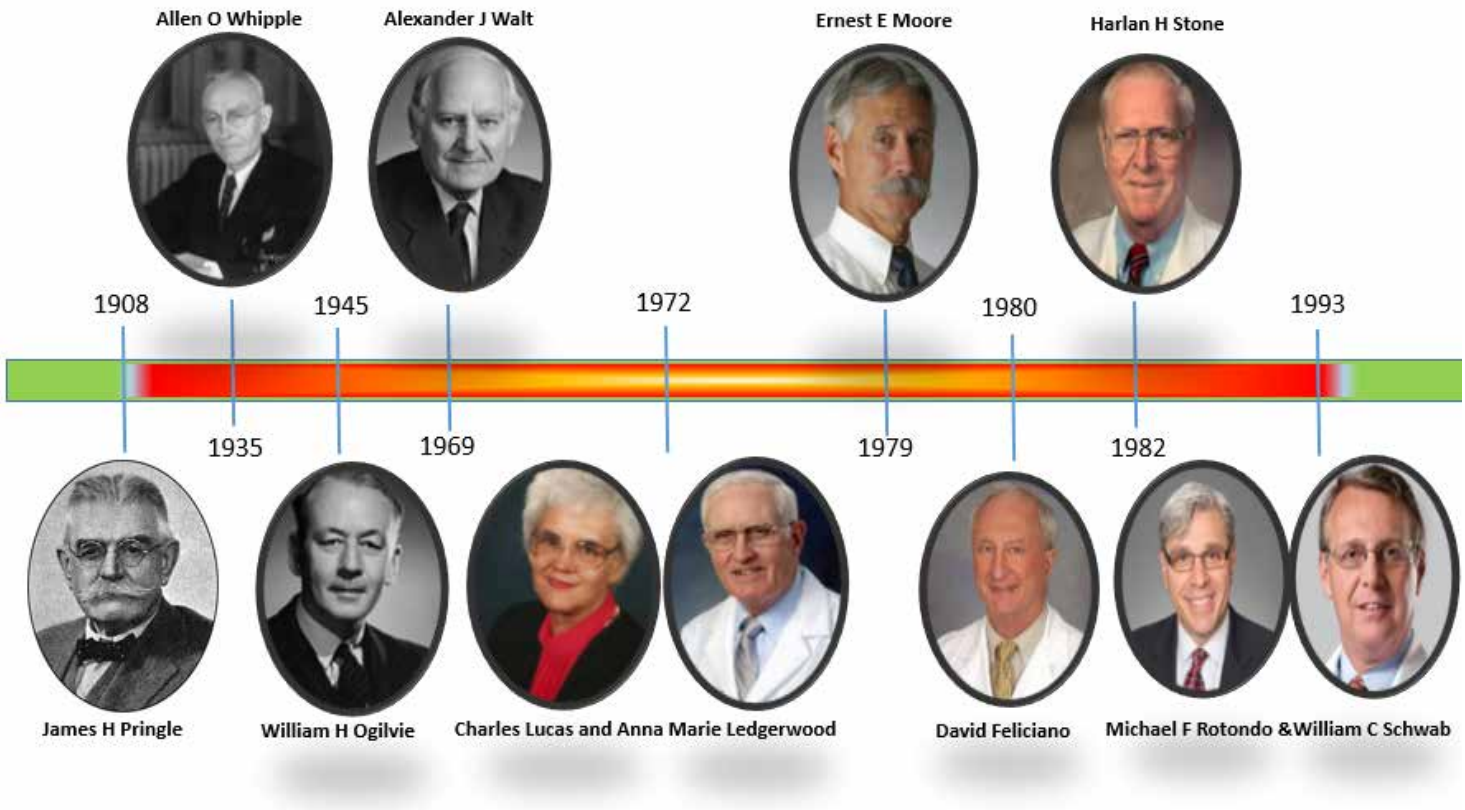


Figure 1: Milestones and Key Figures in the Development of Damage Control Surgery

Recent advancements, including the implementation of permissive hypotension in penetrating trauma and advanced resuscitation techniques almost exclusively damage control hemostatic resuscitation with blood and blood products in modern trauma management have been promoted (1-6), as well temporary bleeding arrest using resuscitative endovascular balloon occlusion of the aorta (REBOA) (7) (although still controversial). There has been an attempt to demonstrate ongoing refinement of DCS trauma care, particularly at the major trauma centers, which emphasizes interdisciplinary collaboration and innovation in severe trauma management [1]. In this article, Ivatury et al state: "*The story of trauma resuscitation (A.K.A damage control surgery for trauma) is like that of many other advances in medicine: described, forgotten, reinvented, ridiculed, and finally accepted. Even after acceptance, the concepts go through periods of neglect and indifference before they are tried and enhanced, till the next advance"* (Figure 2).



Figure 2: Prof. Rao Ivatury

Damage control surgery (DCS) has been a critical aspect of surgery, in both civilian and military[1–7], as it has been a critical component for decades in severely injured patients[1]. Although initially focused on trauma care, the principles of DCS have been successfully adapted to other surgical specialties.

One of the earliest and most notable examples of staging a surgical procedure was depicted brilliantly on the paper by Moore where he reported the entire known history of DCL[8]. He started with staged laparotomy that involved the resection of the pancreatic head for ampullary cancer, first reported by A. O. Whipple in 1935[9]. The concept of using packing to control liver wounds was first introduced by Pringle in 1908[10], while Ogilvie, as one form of DCS mandated stomas for all colorectal war injuries[11]. However, troubling cases of severe complications including hemorrhage, abscesses, and liver necrosis led Madding and Kennedy to advocate against liver packing during World War II[12]. These military guidelines extended through the Korean and Vietnam wars, influencing civilian medical practice as well. A prominent expert in liver trauma of the time, Dr. Walt, declared in 1969 that "there is virtually no place in modern surgery for gauze packing of the liver as sepsis and recurrent bleeding are almost

inevitable sequelae"[13]. However, the strategy of temporary gauze packing was revisited in 1976 by Lucas and Ledgerwood[14]. In this paper the authors evaluated the hemostatic methods employed for managing liver injuries in 637 patients over a five-year period at Detroit General Hospital. The severity of liver injuries, bleeding status, and the specific hemostatic techniques used were reported. Among 637 patients, 325 had either no bleeding or their bleeding was controlled through temporary packing, with none experiencing postoperative rebleeding. Active bleeding correlated with more severe liver injuries and necessitated hemostatic procedures in 312 patients. A year later, their peer Walt published a report dubbed "The Mythology of Hepatic Trauma," dismissing concerns about the method and urging surgeons to use it judiciously without fear for their professional reputation[15]. Enthusiasm toward perihepatic packing grew, gaining momentum and support[16–17]. The next significant development in staged laparotomy came with the landmark study by Stone et al. in 1982, who reported survival rates of 65% of patients with mostly penetrating wounds survived after abdominal packing, compared to just 7% in historical controls[19]. Other groups started reporting similar results[20–22]. By 1993, the University of Pennsylvania trauma group undertook critical evaluations of their experiences, marking a shift towards conceptual refinement[23].

The principles of damage control surgery are pertinent for nearly all surgeons in practice today. While this discussion mainly centers on stages of decision-making for acutely injured patients, similar principles can be applied to surgeries involving critically ill patients facing analogous challenges. Additionally, the concept of staging is applicable to both emergent and scheduled surgeries in diverse anatomical regions, such as the chest, pelvis, neck, and extremities, as well as the abdomen.

DAMAGE CONTROL REPAIR OF WOUNDED SHIP AND DAMAGE CONTROL IN AN INJURED PATIENT

As described above, in modern trauma care, principles of damage control have been adapted to address severe injuries in human patients. Damage control term appears in the naval operations since World War II[24] (https://www.youtube.com/watch?v=VnS_eaSldvs- accessed 11-022025). (Figure 3).



Figure 3: Navy ship in need of damage control

Particularly following the devastating experiences of conflicts like the Battle of Midway and the Kamikaze attacks. Established as a formal discipline in 1945, damage control concept (DCC) focused on the rapid identification, containment, and repair of damage of injured ships during combat situations or during routine training and non-enemy engagement[25]. This paper reports on significant risks associated with major fires on U.S. Navy vessels, especially aircraft carriers, during deployments, and underscores the necessity for preparedness in handling mass casualty situations. An analysis of 246 fire incidents from 1950 to 2020 revealed 27 events resulting in 1,634 casualties, with a mortality rate of approximately 23% among the injured. Like the Navy's approach to DCC to wounded ship, DCS in humans prioritizes rapid stabilization and life-saving interventions for critically injured individuals. It emphasizes quick, decisive actions to manage life-threatening conditions while minimizing long-term complications. Both fields—naval damage control and modern trauma care—underscore the importance of organization, training, and efficient execution in mitigating the consequences of damage, whether to a ship or a human body. The evolution of these practices reflects advancements in technology, training, and understanding of human anatomy and trauma response, demonstrating a shared commitment to effective management of critical situations. While DCS in human patients is effectively designed to manage severe trauma cases, prioritizing immediate life-saving interventions, the benefits of damage control repair in a naval context can be compared to those within a medical setting. Here are some comparable elements between the two approaches:

1. Rapid Stabilization

Navy: In damage control repair, quick interventions to stabilize the vessel, allowing for further repairs to be made without risking additional damage or safety.

Human Patients: DCS aims to immediately critically stabilize a patient, addressing life-threatening conditions to prevent further deterioration, while resuscitation simultaneously with blood and blood products.

2. Repairing Critical Systems

Navy: Focuses on repairing the most critical damage (like hull breaches) to maintain integrity and functionality.

Human Patients: DCS involves prioritizing life-threatening injuries such as securing the airway, achieving hemostasis, binding the fractured pelvis, mobilizing major bone fractures before addressing less critical injuries, which allows for more effective overall treatment, and postponing definitive surgery

3. Minimization of Long-Term Consequences

Navy: Damage control and repair of the wounded ship is designed to minimize long-term deterioration of the ship's performance and capabilities.

Human Patients: DCS controls hemorrhage, contamination reduces the risk of sepsis, and hopefully reduces long-term complications associated with trauma.

4. Collaboration and Teamwork

Navy: Effective damage control and repair rely on the immediate collaboration of crew members with various specialties. This is reflected in the term coined by the Navy, "All hands-on deck.

Human Patients: DCS involves a multidisciplinary approach, with surgeons, emergency physicians, and nursing, anesthesiology and trauma teams all collaborating in order to provide the best care possible. This is where "All hands-on deck" applies to the trauma room."

5. Use of Temporary Measures

Navy: Temporary fixes are be applied to allow continuing operations until more permanent repairs can be made.

Human Patients: DCS often involves temporary measures (e.g., packing a wound, placing shunts to restore blood flow, or placing drains and tubes) until the patient's physiological status is stable enough for definitive surgery.

6. Focus on Recovery and Repair

Navy: After initial damage control, emphasis shifts to repairing the ship fully while ensuring it can continue to operate.

Human Patients: Post DCS patient may undergo subsequent surgeries to address remaining injuries, aligning with a gradual recovery plan.

7. Training and Preparedness

Both the Navy crew members and trauma teams members undergo extensive training to effectively respond to damage control situations and be able to implement DCS protocols and manage critical interventions effectively.

The decision to perform DCS is fundamentally guided by the patient's physiology and the extent of damage sustained; however, it is ultimately at the surgeon's discretion. In making this critical decision, surgeon should consider the principles similarly to those derived from the Navy's four essential elements of a successful damage control program: organization, education, training, and maintenance. A well-organized and structured approach ensures that the surgical team is prepared, and roles are clearly defined, enabling efficient responses to complex trauma cases. Continuous education empowers trauma team with the latest knowledge on trauma management techniques and physiological responses. By integrating these principles into our decision-making process, we surgeons will optimize patient's outcomes and ensure the best possible management of traumatic injuries.

Furthermore, by identifying these comparable elements, we can appreciate how principles of damage control in naval contexts parallel the methodologies in trauma surgery for human patients, emphasizing rapid intervention, stabilization, and teamwork for effective outcomes.

The four fundamental elements of a successful damage-control program on board a ship—organization, education, training, and maintenance are similar in trauma care and DCS in human patients. Each of these elements should be reflected in the practices and protocols used in trauma and emergency surgery, when required.

INDICATIONS AND TIMING FOR DAMAGE CONTROL SURGERY

The damage control approach in trauma management is essential for addressing critically injured patients with specific physiological challenges, such as increased base deficits, elevated lactate levels, and coagulopathy, low body

temperature, acidosis, compromised oxygen delivery, and the need for prolonged operations can increase the risk of complications and mortality and should be considered as indications for DCS[26]. The increased base deficit is particularly alarming in patients with concomitant head injuries, which often exacerbate metabolic derangements. Elevated lactate levels exceeding 5 mmol/L signify anaerobic metabolism and tissue hypoperfusion, warning clinicians of impending or existing shock or organ failure. The initial body temperature is another crucial parameter; a temperature dipping below 35°C, increased prothrombin time greater than 16 seconds coupled with a partial thromboplastin time exceeding 50 seconds points to significant blood clotting issues, a pH <7.18 and need a prolonged operation signals a situation where immediate abbreviated surgical intervention is essential, particularly in complex and I injuries that extensive surgical management.. Collectively, these factors create a comprehensive profile of trauma and critically ill patient who require a damage control approach, emphasizing the urgency of addressing metabolic acidosis, coagulopathy, and the necessity for aggressive management in cases of severe injury and prolonged surgical needs. One specific non-disputable indication for damage control surgery (DCS) is compartment syndrome, although with current practice of minimal fluid resuscitation and liberal use of blood and blood products in damage control strategies among trauma patients, the IAH, once common transient phenomena its incidence has become remarkably low[27]. ACS can occur in the abdomen as well as in other bodily cavities, organs, or extremities following injury



Figure 4: Abdominal compartment syndrome. Intraoperative picture. (Courtesy of Rifat Latifi, MD)

or combination of multiple injuries and over resuscitation (Figure 4, 5)



Figure 5: Massive resuscitation for multiple intraabdominal and extremity injuries, requiring completion amputation of left lower extremity, and open management, closed with "poor man" VAC.(Courtesy of Rifat Latifi, MD)

Specifically, patients with one of the following findings should undergo DCL:

1. Hemodynamic Instability: Critical for patients in shock or presenting with unstable vital signs due to traumatic injuries.

2. Extensive Soft Tissue Damage: Severe injuries may require a thoughtful, staged approach to surgical intervention, necessitating DCS to address significant tissue loss while prioritizing patient stability.

3. Multiple or Complex Injuries: Extensive damage across multiple body systems can complicate surgical management. DCS helps prioritize addressing the most critical threats.

4. Intra-abdominal Hemorrhage as discussed above: Identification and management of heavy internal bleeding in the abdominal cavity typically require DCS strategies that may include packing and temporary closures, but as stated above the bleeding must be controlled and perfusion re-established if possible.

5. Acute Abdominal Compartment Syndrome: (Figure 3,4 This condition can lead to dangerously elevated pressures in the abdominal cavity and have very high mortality if not addressed promptly.

6. Inability to Complete Definitive Surgery: When circumstances—such as a patient's unstable condition—preclude full surgical completion, DCS serves as an intermediary step to ensure initial stabilization before formal repairs.

7. Prolonged Surgery Time: Particularly lengthy surgeries can mandate abbreviated interventions to quickly tackle life-threatening complications and stabilize the patient.

Surgeons must carefully assess critical physiological markers, including instability in hemodynamics, core body temperature (hypothermia), coagulopathy, acidosis, hypocalcemia, and the overall duration of surgery, to decide on abbreviating the surgical procedures efficiently

As an essential part of DCS, major advances have been made in hemostatic resuscitation or damage control resuscitation (DCR). DCR has now become modus operandi in most trauma centers as it has significantly improved outcomes for trauma patients. It effectively reduces the incidence of preventable deaths due to hemorrhage, as well as reduces the need and frequency of damage control laparotomy[22–24]

DCR encompasses a strategic approach aimed at minimizing hemorrhage, addressing life-threatening injuries, and circumventing the lethal triad of hypothermia, coagulopathy, acidosis, as well as hypocalcemia. The American Association for the Surgery of Trauma (AAST) and the American College of Surgeons Committee on Trauma conducted a comprehensive literature review of both prospective and retrospective studies related to DCR practices in trauma patients, from which consensus recommendations were formulated based on the prevailing evidence and expert opinion. The key principles of DCR mirror those of DCS, and it is centered on aggressive hemorrhage control, judicious use of blood products, and activation of massive transfusion protocols (MTP) when necessary. Evidence supports that a well-executed DCR strategy can significantly lower mortality, accelerate the timeline for safe abdominal closure, reduce costs associated with healthcare, and shorten the average hospital stay for trauma patients. DCR is not a singular moment in patient care but a comprehensive process that continues during evaluation, intraoperatively, and even after DCS procedures are performed. This includes early administration of blood products, carefully addressing the lethal diamond throughout the patient's care journey. Permissive hypotension for penetrating trauma has been long promoted[28,29].

IS IT LETHAL TRIAD OR LETHAL DIAMOND?

Most recently and new definition called the "lethal diamond"[30–34] which includes trauma-induced hypocalcemia in addition to the classic lethal triad of hypothermia, acidosis, and coagulopathy. The exploration of the "lethal diamond" in trauma care, which introduces hypocalcemia as a critical factor alongside the well-established lethal triad, highlights a significant yet unresolved contention in emergency and trauma surgery. Despite the growing recognition of the importance of calcium levels in managing exsanguination, these studies findings suggest that hypocalcemia does not offer a substantial advantage in predicting short-term mortality over the traditional triad[33,34]. In addition, there are others who question the elements of lethal triad and some claim that there is only one lethal element in the "diamond" is critical and that is acidosis[35] responsible for the lethality. The study found no notable distinction between the lethal triad and the lethal diamond regarding in 24-hour mortality in severe trauma patients undergoing transfusion. These findings cast doubt on the independent impact of hypocalcemia on early mortality. Furthermore, in the paper "Debunking the lethal triad and delineating damage control surgery," Fabrizio G. Bonanno presents a compelling reevaluation of the lethal triad concept as it relates to damage control surgery (DCS) in trauma cases[35]. Bonanno argues that the traditional emphasis on hypothermia and coagulopathy as critical factors in serious hemorrhagic shock is misplaced, asserting that it is only acidosis that serves as a reliable indicator necessitating DCS intervention. This perspective challenges long-held beliefs in trauma surgery literature and paves the way for a more nuanced understanding of the physiological variables influencing patient outcomes during critical surgical procedures.

Bonanno meticulously analyzes the interactions between macro and microcirculatory dynamics, oxygen levels, and metabolic processes to advocate for a focus on correcting acidosis as the primary measure to mitigate mortality. He underscores that while hypothermia and coagulopathy are often associated with poor outcomes, they do not independently dictate treatment urgency. Instead, he proposes that the timing and techniques surrounding DCS should prioritize the restoration of oxygenation and the management of ischemia-reperfusion injury.

While DCS is well established[36–39], the frequency at which DCS was once being applied has been questioned, which has generated much debate[40]. The study reviewed a substantial cohort of 14,534 trauma patients, noting

a significant decrease in the requirement for DCL procedures—from 36.3% in 2006 to just 8.8% in 2008—accompanied by a marked improvement in mortality rates for those undergoing open laparotomies, which dropped from 21.9% to 12.9%. These findings suggest a more selective approach to DCL can enhance patient outcomes while concurrently reducing healthcare costs, projecting substantial savings in both average costs and charges. Others recently have found that while damage control surgery (DCS) is commonly used in trauma care, its advantages over definitive surgery have not yet been clearly established, partly due to ethical challenges that hinder randomized trials[41]. The decision-making process in DCS is complex, requiring profound knowledge of the patient's physiological status and a keen understanding of the range of injuries or comorbidities present[37].

USE OF NEW TECHNOLOGIES: ANGIOEMBOLIZATION AND REBOA AS ADJUNCT TO DCS

Angioembolization has emerged as a valuable strategy in the context of damage control surgery, particularly, for managing traumatic in solid organ injuries with hemorrhage[42]. By selectively occluding the blood vessels supplying the injured spleen, liver, kidney or surrounding tissues, angioembolization can effectively reduce hemorrhage and stabilize patients in a critical state. Incorporating angioembolization into the damage control approach enables surgeons to prioritize hemostatic control and physiological stabilization during the initial operative phase, thereby improving overall patient outcomes and facilitating subsequent definitive surgical interventions if necessary.

More commonly angioembolization alone is used for liver injuries[43–49] or in combination with open hemorrhagic control. In this study, patients with liver angioembolization (LAE) underwent more percutaneous liver drainage procedures (7.8% vs. 3.3%, p=0.016), as well significant increase in hospital length of stay (17.6 days vs. 14.2 days, p<0.001) and more percutaneous liver drainage procedures (4.3% vs. 0.8%, p=0.002) but less open liver repairs (3.5% vs. 8.3%, p=0.004). For both cohorts, patients undergoing LAE had significantly higher 4-hour transfusion volumes. Another study evaluating LAE[44] found that it was associated with increased morbidity without improving mortality, and these authors suggest that observing these patients is likely a more prudent approach.

The next most common organ to be embolized for major trauma is the spleen[47–50]. In the large study using TQIP data[49] 1,360 patients with severe blunt splenic injuries were analyzed. 328 (24.1%) underwent angioembolization, while 1,032 (75.9%) had a splenectomy. Survival rates were similar for both treatments (hazard ratio = 1.02, P = .49). Notably, about 20% of those who received angioembolization first required a rescue splenectomy within six hours, particularly in cases of grade 5 injuries and additional abdominal trauma. While survival was worse after failed angioembolization compared to successful cases, it was not significantly different from those who had splenectomy first. The authors of this study concluded that angioembolization is a viable treatment option that can provide similar survival outcomes to splenectomy in hypotensive patients with severe blunt splenic injuries. Attempting to preserve the spleen through angioembolization is justified, even if it sometimes leads to complications requiring splenectomy. In addition, renal injuries may be managed by the selective occlusion of blood vessels to minimize hemorrhage as part of damage control surgery[45].

As use of REBOA is becoming more common in hemorrhagic shock particularly in torso injuries[51–54], there is still a major controversy. Most recent study by the Demetriades group[55] analyzed patients with high-grade liver injuries treated with REBOA compared to those managed without it. A total of 252 patients were treated with REBOA and matched with 503 without. The findings revealed that the REBOA group had significantly higher mortality rates (57.9% vs. 35.2%) and greater blood transfusion needs. A recent study of damage control surgery (DCS) combined with Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA) in treating penetrating torso trauma, particularly cases involving non-compressible torso hemorrhage (NCTH) has further questioned use of REBOA[56]. This a systematic review of six studies involving 2,705 patients, revealing improvements in survival and hemorrhage control for some, while others experienced heightened mortality and complications. The findings indicate that while REBOA may offer a survival advantage for certain patients, the results are limited by variability and confounding factors, highlighting the need for further prospective studies. Additionally, risks associated with REBOA include ischemia-reperfusion injury and acute kidney injuries.

Pelvic vascular angio-embolization[57–60] temporary stabilization strategies for severe pelvic fractures are becoming more common. The combination of external fixation and endovascular embolization has been increasingly

recognized as a critical approach in managing pelvic fractures associated with vascular injuries, effectively enhancing hemorrhage control and improving patient outcomes through multidisciplinary collaboration[60]. kidney injury. The article advocates for more structured evaluations to guide clinical practices and research in trauma care, emphasizing the importance of understanding the contexts in which REBOA can be effectively employed. Recent studies, particularly the UK-REBOA trial[61], underscore the complexities involved in implementing Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA) in prehospital environments. These studies point to the necessity of early deployment, careful patient selection, and the reduction of delays to maximize effectiveness. Technological advancements, such as AI-assisted decision-making and automated partial REBOA systems, could improve the implementation of REBOA. The concept of damage control prehospital care prioritizes crucial interventions tailored to the individual patient, aiming for a more efficient approach that decreases on-scene time, thereby potentially reducing preventable deaths from traumatic hemorrhage. Further research is needed to refine protocols and improve outcomes in this critical area of trauma care.

Summary

This paper on damage control surgery presented at the 2nd Professor Rao Ivatury Trauma, Critical Care and Burn symposium" (Figure 2) on (DCS) provides a historical overview of DCS, tracing its evolution and foundational techniques within the realm of trauma management (Figure 1). The paper establishes DCS as a critical intervention for severely injured patients, particularly in addressing life-threatening scenarios characterized by severe hemorrhage and the lethal triad of hypothermia, acidosis, and coagulopathy. It emphasizes that these factors complicate patient outcomes, making prompt recognition and intervention essential. Central to DCS are several guiding principles: rapid assessment and stabilization of life-threatening injuries, immediate control of hemorrhage, arrest and control of contamination and the implementation of temporary measures that allow for the preservation of life until the patient can be stabilized for definitive surgical repairs. Techniques such as hemostatic resuscitation, but allowing some permissive hypotension, and staged laparotomy are critical components of this approach, allowing for a focused response to life-threatening injuries while minimizing the physiological burden on the patient. The relationship between DCS and naval damage control practices is also highlighted, showcasing how principles of rapid stabilization and critical system repairs resonate across both fields. Finally, it discusses the resuscitative endovascular balloon occlusion of the aorta (REBOA), which have further refined the strategies employed in trauma care but needs further studies, and angioembolization of solid organ injuries and major pelvic injuries.

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