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History of the Innovation of Damage Control for Management of Trauma Patients: 1902–2016

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Objective: To review the history of the innovation of damage control (DC) for management of trauma patients.

Background: DC is an important development in trauma care that provides a valuable case study in surgical innovation.

Methods: We searched bibliographic databases (1950–2015), conference abstracts (2009–2013), Web sites, textbooks, and bibliographies for articles relating to trauma DC. The innovation of DC was then classified according to the Innovation, Development, Exploration, Assessment, and Long-term study model of surgical innovation.

Results: The “innovation” of DC originated from the use of therapeutic liver packing, a practice that had previously been abandoned after World War II because of adverse events. It then “developed” into abbreviated laparotomy using “rapid conservative operative techniques.” Subsequent “exploration” resulted in the application of DC to increasingly complex abdominal injuries and thoracic, peripheral vascular, and orthopedic injuries. Increasing use of DC laparotomy was followed by growing reports of postinjury abdominal compartment syndrome and prophylactic use of the open abdomen to prevent intra-abdominal hypertension after DC laparotomy. By the year 2000, DC

surgery had been widely adopted and was recommended for use in surgical journals, textbooks, and teaching courses (“assessment” stage of innovation). “Long-term study” of DC is raising questions about whether the procedure should be used more selectively in the context of improving resuscitation practices.

Conclusions: The history of the innovation of DC illustrates how a previously abandoned surgical technique was adapted and readopted in response to an increased understanding of trauma patient physiology and changing injury patterns and trauma resuscitation practices.

Keywords: abbreviated surgery, damage control, history, staged procedures, surgical innovation, wounds and injuries

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Trauma damage control (DC) is a strategy for management of injured patients that includes DC surgery and DC resuscitation. DC surgery is most often used to control exsanguinating hemorrhage and/or gross contamination in patients with severe physiological derangements or high-risk injury patterns.¹ After operation, the patient is admitted to the intensive care unit (ICU) for ongoing resuscitation before undergoing additional surgery.¹ DC resuscitation is a new concept characterized by rapid hemorrhage control, permissive hypotension, administration of blood products in a ratio approximating whole blood, and minimal use of crystalloid fluids.²

DC is an important development in trauma care and surgery from the latter decades of the last century that provides a valuable case study in surgical innovation. DC changed the age-old surgical dogma that all surgical procedures should be completed before leaving the operating room as it focused on limiting and/or treating deranged physiology before restoring normal anatomy. Its innovation was greatly influenced by the identification of coagulopathy as a principal cause of death in exsanguinating trauma patients and the evolution of trauma resuscitation practices. Its principles have now been used to reshape the practice of other civilian surgical subspecialties, military surgery, and trauma resuscitation itself. In this article, we review the history of the innovation of trauma DC.

METHODS

During the conduct of a scoping review,^{1,3} we searched 11 bibliographic databases (1950–March 1, 2015), abstracts from 5 conferences held between 2009 and 2013, 12 trauma Web sites, Google Scholar, and 30 trauma and surgery textbooks. One author (D.J.R.) selected all articles relating to the innovation of DC surgery and abbreviated surgical (or DC) techniques. This author also reviewed bibliographies of all selected articles and relevant review articles identified during the search. We defined DC surgery as a “multi-step operative intervention, which included a brief initial surgical procedure that aimed to control mechanical bleeding, a massive air leak, and/or gross contamination.”^{1,3}

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The innovation of DC was classified according to the 5 stages of the Innovation, Development, Exploration, Assessment, and Long-term study (IDEAL) model of surgical innovation.^{4,5} We defined an innovative surgical procedure according to the Society of University Surgeons as a “new or modified surgical procedure that differs from current accepted local practice, the outcomes of which have not been described, and which may entail risk to the patient.”⁶ The resultant summary was then sent to 5 senior surgeons (D.V.F., E.E.M., R.R.I., C.E.L., and T.C.F.) who were asked to identify additional references, provide personal reflections and historical photographs, and clarify DC historical events and innovation stages.

History of the Innovation of DC (1902–2016)

Table 1 provides a summary of the IDEAL model stages and principal events that occurred during the innovation of DC. Below, we describe how the “innovation” of DC originated from staged laparotomy for therapeutic liver packing and then “developed” into abbreviated laparotomy using rapid conservative operative techniques. We then detail how subsequent “exploration” resulted in the application of DC to increasingly complex abdominal injury patterns and injuries outside of the abdomen. Subsequently, we describe how increasing indications for and use of DC laparotomy was followed by growing reports of postinjury abdominal compartment syndrome (ACS) and prophylactic use of the open abdomen to prevent intra-abdominal hypertension (IAH) after DC laparotomy. Finally, we describe the current, “long-term study” stage of the innovation of DC, which is characterized by questions about whether DC surgery should be used more selectively in the current era of improving resuscitation practices (ie, DC resuscitation).

Stage 1: Innovation (1902–1983)—Staged Laparotomy for Hepatic and Intra-abdominal Hemorrhage

DC originated from the use of therapeutic packing to control hepatic hemorrhage. In contrast to resuscitative packing (where packs are used to check intraoperative bleeding for a short period of time), therapeutic packing refers to the prolonged (intra- and postoperative) use of packs to tamponade hemorrhage.¹

In the early 1900s, before and after World War I, hepatorrhaphy with deep mattress sutures, gauze packing, and open drainage were commonly used to manage liver injuries.^{7,8} Pringle reported managing a difficult-to-access injury to the right hepatic lobe with suprahepatic packing in 1902.⁹ He subsequently concluded that “[t]he permanent arrest of hepatic hemorrhage is, in my opinion, best effected by ligation of the liver tissue in mass in every case where that is possible, but in some cases it may not be practicable and then we will have to rely solely upon packing.”⁹

Most surgical texts published during the early 1900s recommended that gauze packs be stuffed directly into hepatic tears to facilitate hemostasis (sometimes with the parenchyma loosely approximated overtop, creating a “tampon”).^{8,10,11} These “intrahepatic” packs would commonly be removed days later at the bedside.^{12,13} As packs frequently became adherent to the raw hepatic parenchyma, removal was associated with significant pain and often led to recurrent hemorrhage.¹¹

Experiences using intrahepatic packing in a large number of trauma patients during World War II led Madding, Kennedy, and other members of the Second Auxiliary Surgical Group to condemn its use by the end of the war.^{14,15} In 1971, Madding and Kennedy reported that: “[d]isastrous hemorrhage followed the removal of gauze packs. Abscesses occurred within the liver or in the perihepatic spaces, and hepatic necrosis was observed in areas that had been packed. Peritonitis, hepatitis, fistulas, and numerous other complications followed.”⁸ Therapeutic intrahepatic packing was

therefore largely abandoned during the Korean and Vietnam wars,¹⁵ during which time many surgeons viewed its use as a sign of poor surgical skills. Most surgeons instead attempted to control hepatic hemorrhage using simple (eg, hepatorrhaphy) or advanced (eg, hepatorrhaphy with selective vascular ligation, selective hepatic artery ligation, wedge resection, and/or segmentectomy or lobectomy) methods of mechanical hemostasis.^{13,15–20} These and other improvements in management of these patients were associated with a reduction in hepatic trauma-related mortality from 66% in World War I to 9% in the Vietnam war.²¹

The use of therapeutic liver packing was resurrected in the late 1970s when new, yet limited indications for its use were suggested by Lucas and Ledgerwood.^{15,20} In a study of 637 patients undergoing operation for liver injuries at the Detroit General Hospital between 1968 and 1973, the authors reported using therapeutic “perihaptic” packing in 3 patients.²⁰ One had an abdominal gunshot wound resulting in a trough along the anterior margin of both hepatic lobes, and the other 2 injuries requiring extension of the incision into the right chest.²⁰ Packs were removed at reoperation 3 to 5 days later, and all patients survived.²⁰ Lucas and Ledgerwood suggested that perihaptic packing had “a very important role for the temporary control of bleeding liver wounds which would otherwise require hepatectomy when the surgeon is not mentally or technically qualified to perform such a procedure.”²⁰

Dr Alexander J. Walt, Chairman of the Department of Surgery at Wayne State University, later reported in 1978 that packing was effectively used to treat at least 5 patients with refractory hepatic hemorrhage in the preceding 15 years at the Detroit General Hospital.²² Calne et al²³ also reported that 4 patients presenting to peripheral hospitals in England with massive hepatic hemorrhage were successfully managed with conservative initial surgery and packing, which facilitated transfer to a definitive care center. In the Founder’s Lecture presented at the 18th Annual Meeting of the Society for Surgery of the Alimentary Tract in 1977, Dr Walt addressed the widespread negative bias toward hepatic packing by stating: “I have no wish to revivify the idea of the pack as a desirable standard practice. On the other hand, the judicious surgeon who chooses this method should in no way fear the whispered loss of his surgical manhood.”²²

Indications for perihaptic packing grew after nonmechanical (coagulopathic) hemorrhage was identified as the principal cause of death in patients undergoing operation for hepatic trauma.¹⁵ This complication was thought to occur because of massive transfusion of banked blood, disseminated intravascular coagulation, excessive fibrinolysis, platelet dysfunction, and/or defective synthesis of clotting factors.^{21,24} In 1978, Clagett and Olsen²⁴ observed that 52% of patients with major liver trauma at Wayne County General Hospital developed coagulopathy. Elerding et al²¹ subsequently reported that coagulopathy was the cause of 82% of deaths following hepatic trauma at the Denver General Hospital and recommended routinely obtaining coagulation studies in these patients and prophylactic administration of plasma and platelets to patients receiving massive transfusion.²¹

In a subsequent publication, the Denver General group observed that exsanguinating hemorrhage was frequently associated with the onset of a “viscous cycle” (sometimes also referred to as the “bloody viscous cycle” or “lethal triad”) of hypothermia, acidosis, and coagulopathy.²⁵ They hypothesized that development of hypothermia and metabolic acidosis aggravated an already evolving coagulopathy.^{25–27} In retrospect, each of the elements of the viscous cycle were likely made worse by resuscitation practices at the time, including prompt administration of large volumes of crystalloid fluids to injured patients, a practice which was based on supportive preclinical experiments led by Shires in the 1960s.^{28,29}

TABLE 1. IDEAL Stages of the Innovation of Trauma Damage Control

Stage	IDEAL Description ^{4,5}	Principal Events in the Innovation of Damage Control
1 Innovation	Descriptions of the first use of the procedure (technical achievements, disasters, and successes) by a small number of surgeons, prompted by the need for a new solution to a clinical problem	<p>In the early 1900s, intrahepatic gauze packing was commonly used to manage liver wounds. Experience with managing a large number of trauma patients with intrahepatic packing during World War II led Madding, Kennedy, and others to condemn its use by the end of the war because of associated adverse events.</p> <p>Therapeutic intrahepatic packing was largely abandoned during the Korean and Vietnam wars, during which time many surgeons viewed its use as a sign of poor surgical skills.</p> <p>In 1976, Lucas and Ledgerwood described the effective use of therapeutic perihepatic packing in 3 severely injured patients.</p> <p>Walt reported in 1978 that packing was effectively used to treat at least 5 patients with refractory hepatic hemorrhage in the preceding 15 years at the Detroit General Hospital.</p> <p>Elerding et al and Kashuk et al identified coagulopathy as the major contributor to refractory hemorrhage in trauma patients.</p> <p>Feliciano et al reported that 9 of 10 patients with liver injury and diffuse coagulopathic hemorrhage or expanding subcapsular hematomas survived to discharge after being managed with therapeutic perihepatic packing.</p> <p>Stone et al reported performing staged laparotomy that sought to create “abdominal tamponade” in patients who developed “major coagulopathy” during operation.</p> <p>In the early 1980s, several authors reported data suggesting that staged laparotomy had a survival benefit for management of exsanguinating trauma patients.</p> <p>By 1984, 8 American trauma centers reported that 4% of all patients with hepatic trauma at their center were being managed with staged laparotomy for therapeutic perihepatic packing.</p> <p>In 1988, Feliciano et al hypothesized that use of “rapid conservative operative techniques” may have contributed to reduced operative time and postoperative complications and improved survival in patients with abdominal gunshot wounds.</p> <p>Subsequent support of the effectiveness of rapid conservative operative techniques led to the application of the DC concept to other, more complicated abdominal injury patterns, and reports of a growing number of rapid conservative operative techniques.</p> <p>In 1993, Rotondo, Schwab, and the group at the University of the Hospital of Pennsylvania proposed that abbreviated laparotomy be called “damage control” and defined the stages of abbreviated laparotomy.</p> <p>In the 1990s, an increasing number of reports of rapid conservative operative techniques appeared in the literature.</p> <p>By the year 1998, >1000 critically injured patients had been reported to be managed with DC laparotomy.</p> <p>In the early 1980s, the first reports emerged describing the occurrence of abdominal compartment syndrome after major abdominal surgery, followed by a large increase in the number of reported cases of abdominal compartment syndrome after DC laparotomy, prophylactic use of the open abdomen to prevent intra-abdominal hypertension after DC laparotomy, and increasingly innovative methods to manage the open abdominal wound.</p> <p>The DC concept was extended outside of the abdomen to the management of thoracic and peripheral vascular injuries.</p> <p>DC surgery was widely adopted by trauma centers and recommended in surgical journals, textbooks, and teaching courses.</p> <p>Surgeons and industry developed methods to achieve staged abdominal closure during the index hospitalization.</p> <p>Increased research and heightened awareness and education relating to intra-abdominal hypertension/abdominal compartment syndrome may have led to a decline in the incidence of postinjury abdominal compartment syndrome in the early 21st century.</p> <p>The DC principle was applied to military surgery and other civilian surgical specialties.</p> <p>Questions about the effectiveness and safety of the procedure in modern trauma care and whether the procedure should be used more selectively in the current era of improving resuscitation practices</p>
2a Development	The procedure has been proposed but the details have not yet been completely worked out, the technology has been deemed probably safe by the innovators and can be tested more extensively, and a few opinion leaders are beginning to use it, which facilitates its diffusion. Technical modifications to the procedure are common at this stage	
2b Early dispersion and exploration	Individual learning curves are progressing quickly	
3 Assessment	The procedure is now part of many surgeons’ practices and is becoming standard of care	
4 Long-term implementation and monitoring	Relates to how well the procedure is doing in practice	

TABLE 1. (Continued)

Stage	IDEAL Description ^{4,5}	Principal Events in the Innovation of Damage Control
	<p>Borgman et al reported that a high plasma:PRBC ratio was independently associated with improved survival in trauma patients requiring massive transfusion admitted to a combat support hospital in Iraq</p> <p>The United States Army's Institute of Surgical Research Conference used the above to support the concept of "DC resuscitation"</p> <p>A randomized controlled trial compared a 1:1:1 versus 1:1:2 ratio of plasma:platelets:PRBCs and reported similar 24-hour and 30-day mortality. However, subgroup analyses suggested that more patients in the 1:1:1 group achieved hemostasis, and fewer experienced death due to exsanguination at 24 hours</p> <p>Studies currently required to further delineate the role of DC surgery in the context of improving trauma resuscitation practices</p>	
	DC indicates damage control; IDEAL, Innovation, Development, Exploration, Assessment, and Long-Term study; PRBCs, packed red blood cells.	

In 1981, Feliciano et al¹³ reported that 9 of 10 patients at the Ben Taub General Hospital in Houston, TX, with major hepatic injuries and diffuse coagulopathic hemorrhage or expanding subcapsular hematomas survived to discharge after being managed with therapeutic perihepatic packing as a "last desperate maneuver." The authors suggested that therapeutic perihepatic packing may be a valuable adjunct for control of hepatic hemorrhage in highly selected patients who develop a coagulopathy after use of standard mechanical techniques of hepatic hemostasis.¹³ They also suggested that therapeutic perihepatic packing could be used instead of hepatic lobectomy to manage extensive subcapsular hematomas or bilobar parenchymal injuries.¹³

The final step of the innovation of DC surgery occurred at the Grady Memorial Hospital in Atlanta, GA, after Stone et al³⁰ hypothesized that "the same principle [ie, compression] might prove to be effective even when a bleeding diathesis had led to a relatively diffuse hemorrhage throughout the entire peritoneal cavity." In 1979, these authors began performing staged laparotomy (ie, laparotomy with planned reoperation after a period of ongoing resuscitation in the ICU) that sought to create "abdominal tamponade" with packing in patients who developed "major coagulopathy" during operation.³⁰ The protocol included: "... immediate termination of the operation; repair of only those vessels vital to survival, with ligation of all others; ligation of bowel ends. . . The spleen and kidney, if bleeding, were removed unless renal injury was bilateral, for which the kidneys were packed. Ureteral wounds were managed by simple ligation, while the bladder was closed with a one-layered purse-string suture. If the pancreas had been resected, the stump was ligated with an umbilical tape. Gallbladder wounds were closed by a purse-string suture, yet major bile duct injuries were merely isolated by laparotomy pack."³⁰ At the conclusion of abbreviated laparotomy, "an average of nine laparotomy pads (range of 4–17) then were packed tightly into the peritoneal cavity, and the abdomen was closed under considerable tension."³⁰ As compared to a historical survival estimate of 7% (1 of 14) among similarly injured patients managed "by standard procedures directed toward reversal of the bleeding diathesis plus completion of all details of the operative procedure", 65% (11 of 17) of patients survived when managed with staged laparotomy.³⁰

Stage 2a: Development (1984–1993)—Abbreviated Laparotomy Using Rapid Conservative Operative Techniques

The subsequent stage of the innovation of DC included moving from a predominantly staged to an abbreviated laparotomy; the application of DC to other, more complicated abdominal injury patterns; and the proposal that the approach be called "damage control."

Use of staged laparotomy for management of trauma patients became widely accepted within 5 years of the publication by Stone et al,³⁰ with several authors reporting supporting data.^{11,31–33} At the 1985 meeting of the American Association for the Surgery of Trauma (AAST), Drs Feliciano, Ivatury, Walt, and Pachter presented and discussed papers reporting on patients managed with therapeutic perihepatic packing at Ben Taub General Hospital and Lincoln Medical and Mental Health Center in the Bronx.^{11,32} They concluded that perihepatic packing was a potentially life-saving procedure for a small subset of patients with severe hepatic injuries when other methods failed to achieve hemostasis.³² The above findings initiated widespread practice change: by 1984, 8 American trauma centers reported that 4% (range, 0%–10%) of all patients with hepatic trauma at their center were being managed with therapeutic perihepatic packing.³⁴



FIGURE 1. Temporary abdominal closure using towel clips. Reprinted with permission from ref.³⁶ Copyright (1989), with permission from Elsevier.

Shortly thereafter, it was noted that staged laparotomy in critically injured patients might also improve outcomes by abbreviating the length of the index operation.³⁵ In 1988, Feliciano et al³⁵ described their experiences managing 300 consecutive patients with abdominal gunshot wounds using “rapid conservative operative techniques.” These included nonresectional management of hepatic and splenic injuries, primary repair of small and large bowel injuries, rapid control of abdominal vascular injuries, and use of towel clips to quickly close the skin after operation in patients with hypothermia, non-mechanical bleeding, and/or marked abdominal visceral distention (Fig. 1).^{35,36} The authors hypothesized that abbreviated operative techniques may have contributed to reduced operative time and postoperative complications and improved survival during the study period.³⁵

Support of the effectiveness of rapid conservative operative techniques led to the application of the DC concept to other abdominal injury patterns and reports of a growing number of abdominal DC interventions. In 1990, Eastlick et al³⁷ reported managing a patient with an abdominal gunshot wound traversing the liver and destroying the pancreaticoduodenal complex with perihepatic packing and pancreaticoduodenectomy followed by reoperation for pancreaticobiliary and gastrointestinal reconstruction 36 hours later. Thereafter, Burch et al³⁸ described using a number of “unorthodox” surgical techniques (ligation of enteric injuries, retained vascular clamps, and temporary intravascular shunting [TIVS]) among 200 critically injured patients admitted to Ben Taub General Hospital (Figs. 2 and 3). As 66 (33.0%) of these patients survived, the authors suggested that prompt termination of laparotomy using abbreviated surgical techniques was a “rational approach to an apparently hopeless situation.”³⁸



FIGURE 2. Temporary abdominal closure using a silo/Bogotá bag in a patient with retained vascular clamps on multiple pelvic bleeders after a transpelvic gunshot wound. Image reproduced with permission from ref.²⁶ Copyright Elsevier (1991).



FIGURE 3. Temporary intravascular shunting of a combined iliac artery and ureter injury in a patient with an abdominal gunshot wound.

The final step of the development of DC occurred in 1993 when Rotondo, Schwab, and the group at the Hospital of the University of Pennsylvania³⁹ proposed that abbreviated surgery be called “damage control.” They suggested that DC could have broad use given the increasing number of patients presenting to American trauma centers with multivisceral penetrating injuries from larger caliber, higher muzzle velocity, semiautomatic weapons.^{39–41} Schwab, a former officer in the US navy, adopted the term “damage control” from the navy where it represents “the capacity of a ship to absorb damage and maintain mission integrity,” which, in trauma surgery, corresponds to “those maneuvers designed to ensure patient survival.”^{42,43} Surgeons at the University of Pennsylvania also more specifically defined the stages of abbreviated laparotomy as DC 1 (immediate laparotomy for control of hemorrhage and contamination followed by temporary abdominal closure [TAC] and transfer to the ICU), DC 2 (resuscitation in the ICU with the goal of maximizing hemodynamics and correcting hypothermia, acidosis, and coagulopathy), and DC 3 (reoperation for definitive repair of abdominal injuries and closure of the abdomen).^{39,44} These authors and others also later suggested adding the stages DC 0 or “damage control ground zero” (those interventions provided within the prehospital and trauma admissions area before operation) and DC IV (definitive abdominal reconstruction).⁴⁵

Stage 2b (Part 1): Early Dispersion (1994–2000s)— The DC Laparotomy Learning Curve and Growing Reports of Postinjury Abdominal Compartment Syndrome

In the early dispersion stage of the innovation of DC, increasing indications for and use of DC laparotomy were followed by growing reports of postinjury ACS, prophylactic use of the open abdomen to prevent IAH after DC laparotomy, and the development of increasingly innovative methods to manage the open abdominal wound.

This stage began with the development of new rapid conservative operative techniques. Hirshberg et al⁴⁶ and the group at the Ben Taub General Hospital reported rapidly removing injured kidneys and using balloons to tamponade bleeding internal iliac vessels.⁴⁶ Poggetti et al⁴⁷ subsequently described using an improvised balloon tamponade device to control massive hemorrhage from bilobar transfixing hepatic gunshot wounds (Fig. 4).⁴⁸ Reilly et al⁴⁹ reported that a patient with complete transection of the proximal superior mesenteric artery, a nonviable-appearing midgut, and hypothermia, acidosis, and coagulopathy survived after TIVS was used to rapidly terminate operation and allow for rewarming and correction of coagulopathy in the ICU.⁴⁹ Finally, Azimuddin et al⁵⁰ and Coburn⁵¹ suggested interventions that could be used to temporize injuries to the ureter and bladder, including delayed ureteroureterostomy and unilateral and bilateral externalized ureteral stenting. By 1998, there were reports of >1000 critically injured patients treated with DC laparotomy, of which an impressive 50% survived.⁵²

In the early 1980s, the first reports emerged describing ACS after major abdominal surgery. Richards et al⁵³ reported resolution of renal failure after laparotomy and evacuation of intra-abdominal hematomata in 4 postoperative patients with tense abdominal distention. Kron et al⁵⁴ subsequently described that decompressing the abdomen in postoperative abdominal surgery patients with a bladder pressure >25 mm Hg seemed to reverse oliguric renal failure and prevent death. Finally, in 1989, Fietsam et al^{55,56} reported 4 patients who developed a condition that they termed “intra-abdominal compartment syndrome” (increased peak inspiratory and central venous pressures, oliguric renal failure, and massive abdominal distention) after repair of ruptured abdominal aortic aneurysms and administration of a massive volume of resuscitation fluids.



FIGURE 4. Penrose and red rubber Robinson catheter tamponade of a central hepatic gunshot wound. Image reproduced with permission from ref.⁴⁸ Copyright Wolters Kluwer Health (2011).

The above was followed by reports of a large number of cases of ACS after DC laparotomy.⁵⁶ Hemorrhagic shock was hypothesized to result in an ischemia-reperfusion injury of the bowel, increased intestinal permeability, and heightened sequestration of fluid in the bowel wall.⁵⁷ This process, when combined with large volume fluid resuscitation and significant intra-abdominal blood/ongoing intra-abdominal bleeding, tight intra-abdominal packing, and a tense, noncompliant abdominal wall, significantly increased intra-abdominal pressure.^{57,58} Forced closure of the skin and/or fascia in this setting (as was common at the time) was reported to frequently produce fascial necrosis and/or postoperative ACS.^{59,60} Some have hypothesized that the postinjury ACS epidemic was produced by resuscitation practices at the time that emphasized administration of large volumes of crystalloid fluids and use of supranormal trauma resuscitation in injured patients.^{56,61,62}

To prevent postoperative ACS, studies appeared supporting the use of prophylactic abdominal decompression after abbreviated laparotomy.^{59,63,64} In 1993, Morris et al⁶⁵ at Vanderbilt University recommended early abdominal decompression for patients who developed ACS after abbreviated laparotomy given the high mortality associated with the condition. At the 57th Annual Meeting of the AAST, Ivatury et al⁶⁵ reported observing gastric mucosal acidosis in 70 critically ill patients with IAH who underwent abbreviated laparotomy at the Lincoln Medical & Mental Health Center before the development of ACS. They hypothesized that, when left uncorrected, postoperative IAH may induce splanchnic hypoperfusion and gut mucosal acidosis resulting in ACS and therefore advocated for TAC of the “open abdomen” to prevent IAH/ACS after DC laparotomy.⁶⁵

Original TAC methods provided “simple containment of the viscera.”⁶⁶ Complications of the earlier method of towel clip closure included evisceration of small bowel (see Figure in Supplemental Digital Content 1, <http://links.lww.com/SLA/B30>) and postoperative ACS.²⁶ Methods later used included bridging silos.²⁶ Dr Oswaldo Borraez developed a commonly used temporary silo (the “Bogotá bag”) while he was a surgical resident training in the Hospital San Juan de Dios in Bogotá, Colombia, South America. This silo commonly consists of a sterilized 3 L genitourinary irrigation bag cut at the seams, unfolded, and then anchored to the skin of the

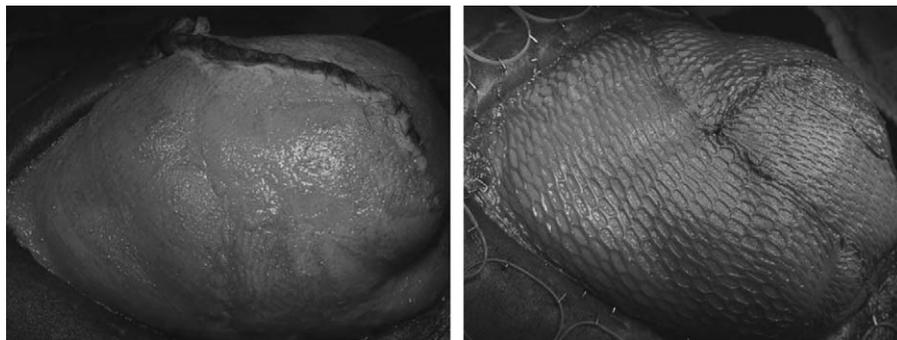


FIGURE 5. Use of a planned ventral hernia in a patient with secondary abdominal compartment syndrome after a ruptured descending thoracic aortic injury secondary to a motor vehicle collision. Appearance of the absorbable mesh prosthesis before its removal (left) and the subsequent application of a split-thickness skin graft to the granulated open abdomen (right). Images reproduced with permission from ref.⁷¹ Copyright McGraw-Hill Education (2000).

abdominal wound (see Figure in Supplemental Digital Content 2, <http://links.lww.com/SLA/B30>).⁶⁷ Other simple TAC methods used included bridging absorbable or synthetic meshes, placement of a moist surgical towel over the viscera (covered by an adherent plastic drape over the skin),⁶³ or a rayon cloth sheet/fluff gauze/retention suture “pack”.⁶⁸ Zippers and slide fasteners were also used in some centers for those requiring repeated abdominal exploration (see Figure in Supplemental Digital Content 3, <http://links.lww.com/SLA/B30>).

If the abdominal wound was not closed within 10 to 15 days, dense adhesions developed between bowel loops and the undersurface of the abdominal wall, obliterating the intraperitoneal space and creating a “frozen abdomen.”⁶⁶ This process, when combined with lateral retraction of the abdominal fascial edges, precluded definitive abdominal closure. These wounds were frequently managed with a “planned ventral hernia” after the report by Fabian et al⁶⁹ at the University of Tennessee Health Science Center in 1994 (Fig. 5).^{70,71} In this technique, a temporary prosthesis (eg, polypropylene or polyglactin 910 mesh or expanded polytetrafluoroethylene) is sutured between the fascial edges to bridge the defect.⁶⁹ This prosthesis is then removed 14 to 21 days later and the wound covered with a split-thickness skin graft or mobilized native skin flap.⁶⁹ Finally, 6 to 12 months after hospital discharge, when the skin graft can be pinched off the underlying viscera, the graft is removed and the abdomen closed with a permanent prosthesis or components separation technique.⁶⁹

In 1995, Brock, Barker, and Burns⁷² at the University of Tennessee College of Medicine described using a “vacuum pack” for TAC after DC laparotomy. This technique, which was a modification of that suggested by Schein et al⁷³ in 1986 to manage intra-abdominal sepsis, consisted of a visceral drape covered by surgical towels, 2 closed suction drains connected to wall suction, and an adhesive film dressing. The visceral drape served as a physical barrier that prevented adhesions between the bowel and abdominal wall, which extended the window of opportunity for definitive abdominal closure to as long as a month after initial operation.⁶⁶ This relatively simple solution later allowed for creation of staged abdominal reconstruction techniques that could be used to achieve progressive abdominal closure during repeated laparotomies.⁶⁶

Stage 2b (Part 2): Exploration (1994–2000s)— Extension of the Concept Outside of the Abdomen

The exploration stage of the innovation of DC was characterized by its adaptation to manage injuries outside of the abdomen, including those to the peripheral vasculature and thorax.

In the early 1990s, before the promulgation of DC terminology, Feliciano et al⁷⁴ described using balloon catheters to effectively control life-threatening hemorrhage from cardiac and vascular

wounds. This approach was later reported by Gilroy et al,⁷⁵ Hirshberg et al,⁴⁶ and others⁷⁶ to be effective for controlling a number of difficult-to-access bleeding sites in the trauma bay and/or the operating room. These include zone I and III of the neck; the face, pharynx, heart, and internal carotid artery at the base of the skull; and the innominate, axillary, subclavian, iliac, femoral, and popliteal vessels (Fig. 6).⁴⁸

In 1994, Scalea et al⁷⁶ reported using DC to manage a patient with an extremity vascular injury at the SUNY Health Science Center in Brooklyn, NY. The patient presented with acidosis and coagulopathy after a stab wound produced brisk arterial bleeding from deep in the thigh that persisted despite attempts at surgical hemostasis.⁷⁶ The wound tract was packed, the skin temporarily closed, and the patient transferred to the angiography suite for embolization of a branch of the profunda femoris artery.⁷⁶ Others later described simple vascular repair techniques that could be used in hypothermic and coagulopathic patients with truncal and peripheral vascular injuries, including lateral repair, ligation, TIVS, and/or rapid primary amputation.⁷⁷

During the same year, Hirshberg et al⁴⁶ described rapid measures to manage injuries in the chest. These included pleural cavity packing, nonanatomic pulmonary resections, and rapid lobectomy or pneumonectomy using linear stapling devices.⁴⁶ Another thoracic DC intervention suggested as an alternative to anatomic



FIGURE 6. Foley and Fogarty balloon catheter tamponade of an internal carotid artery transection after a stab wound to the preauricular area of the face. Image reproduced with permission from ref.⁴⁸ Copyright Wolters Kluwer Health (2011).

lobectomy for patients with parenchymal lung bleeding was pulmonary tractotomy.^{78,79} In this technique, the lung overlying a pulmonary parenchymal wound is divided between vascular clamps or using a linear cutting stapler, thereby allowing small injured vessels and bronchi underneath to be selectively ligated.^{78,79} Other thoracic DC interventions that have been reported include simultaneously stapled pneumonectomy (as an alternative to conventional anatomic lobectomy)⁸⁰ and the pulmonary hilar twist (a 180-degree rotation of the pulmonary hilum to control hemorrhage and prevent air embolism after severe lung trauma requiring thoracotomy).⁸¹

Stage 3: Assessment (Early 1990s–Late 2000s)—Widespread Adoption of DC Surgery and Heightened Postinjury ACS Research, Education, and Preventive Efforts

The assessment stage of the innovation of DC surgery was characterized by the widespread adoption and recommendation of the procedure in surgical journals, textbooks, and teaching courses; increased research, education, and awareness relating to IAH/ACS; the creation of methods to achieve definitive abdominal closure during the index hospitalization; and the application of the DC concept to military surgery and other civilian surgical specialties, including general, orthopedic, vascular, and neurological surgery.

In 2000, Scalea et al⁸² reported that DC had been “adopted by virtually every trauma center in this country” whereas in 2006 Sutton et al⁸³ stated that “its overall benefit is indisputable.” As many DC-related complications stemmed from the inability to close the open abdominal wound, surgeons and industry developed methods that could be used to achieve staged abdominal reconstruction during the index hospitalization. These included the Wittmann patch (Starsurgical, Burlington, WI),⁶⁴ negative pressure wound therapy devices, vacuum-assisted sequential fascial closure,⁸⁴ vacuum-assisted wound closure and mesh-mediated fascial traction,⁸⁵ and dynamic retention using sutures or the Abdominal Reapproximation Anchor device (Canica Design Inc, Almonte, Ontario, Canada).

By the early 2000s, the importance of postinjury ACS was well recognized. This stimulated formation of the World Society of the Abdominal Compartment Syndrome in 2004 (www.WSACS.org). Their reported goal was to “promote research, foster education, and improve the survival of patients with IAH and ACS.” This group published expert consensus definitions in 2006,⁸⁶ clinical practice guidelines in 2007,⁸⁷ and recommendations for research in 2009.⁸⁸ Some authors have hypothesized that increased research and heightened awareness and education relating to IAH/ACS have led to the decreased incidence of postinjury ACS observed in the last 15 years.⁵⁶

During this stage, the DC principle was also applied to military surgery and other civilian surgical specialties. In Operations Iraqi Freedom and Enduring Freedom in Afghanistan, injured patients were transported by helicopter to a trauma facility in the combat zone after receiving battlefield treatment.^{89,90} At these facilities, resuscitative and stabilizing procedures, including intra-abdominal packing, rapid resection of bowel injuries, TIVS, and external fixation of long bone injuries, were completed before patients were transported to more advanced care locations.^{89–91} Scalea et al⁸² suggested in 2000 that external fixation of long bone fractures or “DC orthopedics” should be used instead of immediate intramedullary nailing in patients with multiple injuries. Pape et al⁹² subsequently reported that polytrauma patients with a femur fracture experienced a reduced postprocedure inflammatory burden when managed with external fixation instead of immediate intramedullary nailing. After further treatment at military trauma facilities, patients were transported to

Landstuhl Regional Medical Center in Germany.⁹⁰ Through the Senior Visiting Surgeon Program (of the AAST and American College of Surgeons’ Committee on Trauma), many civilian trauma care leaders in the United States volunteered to participate in the care of injured soldiers and contribute to education at the center, including about the principles and practice of DC.⁹⁰

Long-term Implementation and Monitoring (Late 2000s–2016): Selective DC Surgery in the Current Era of Improving Resuscitation Practices

The current stage of the innovation of DC surgery is characterized by questions about the effectiveness and safety of the procedure in modern trauma care and whether it should be used more selectively in the current era of improving resuscitation practices.

Although widely believed to be effective when appropriately indicated, no adequately controlled studies have been performed to evaluate DC surgery.³ Further, the procedure has been reported to be associated with several potentially severe complications (eg, intra-abdominal abscesses/sepsis, massive ventral hernias, and enteroatmospheric fistulae), a substantial risk of readmission to hospital and need for subsequent surgical procedures, decreased physical and mental health, and a reduced quality of life among survivors.^{93–97} Studies have also recently reported data suggesting important variation in the use of DC surgery exists across trauma centers and that the procedure may be overused.^{98–100} Finally, some authors have suggested that clinical outcomes may improve with more selective use of DC surgery.⁹⁸

Authors have also recently hypothesized that trauma resuscitation strategies that focus on rapid hemorrhage control, prevention and/or correction of coagulopathy, and avoidance of over-resuscitation with crystalloid fluids may reduce the need for DC surgery in the future.^{101–103} In 2003, Brohi et al¹⁰⁴ conducted a retrospective cohort study of 1088 severely injured patients and observed that 33% had prolonged clotting times upon presentation to hospital that were independent of the volume of intravenous fluids administered. These authors suggested that there is “a common and clinically important acute traumatic coagulopathy” that occurs “before significant fluid administration, that may be attributable to the injury itself.”¹⁰⁴ This was followed in 2007 by a retrospective cohort study by Borgman et al¹⁰⁵ of 246 trauma patients requiring massive transfusion who were admitted to a combat support hospital in Iraq. Borgman et al¹⁰⁵ reported that a high plasma: packed red blood cell (PRBC) ratio was independently associated with improved survival, primarily by decreasing death due to hemorrhage. These results were used by the United States Army’s Institute of Surgical Research Conference to support development of the concept of “damage control resuscitation.”¹⁰⁶ This group recommended immediate delivery of fresh frozen plasma, platelets, and PRBCs in a 1:1:1 ratio to injured patients requiring massive transfusion based on the rationale that a 1:1:1 ratio mimics the composition of whole blood.^{106,107} DC resuscitation is recommended to be delivered across the continuum of time-sensitive care for critically injured patients and therefore has influenced trauma resuscitation research and practice in the prehospital, Emergency Department, operating room, and ICU settings. Subsequent observational studies of DC resuscitation reported mixed yet frequently similar observations to that of Borgman et al.¹⁰⁵ Most recently, the PROPPR randomized controlled trial compared a 1:1:1 and a 1:1:2 ratio of plasma: platelets: PRBCs and reported similar 24-hour and 30-day mortality for the 2 study groups.² However, subgroup analyses suggested that more patients in the 1:1:1 group achieved hemostasis, and fewer experienced death due to exsanguination at 24 hours.²

CONCLUSIONS

DC is an important innovation in trauma care and surgery during the last century. The history of DC provides a valuable illustration of surgical innovation, which highlights how a surgical technique that had previously been abandoned because of adverse events was subsequently adapted and readopted in response to an increased understanding of trauma patient physiology and changing patient injury patterns and trauma resuscitation practices. Studies are currently required to further delineate the role of DC surgery in the context of improving trauma resuscitation practices.

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