Endovascular Capability for Wartime Injury

Lessons learned and implications for future innovation and practice.

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> "A new era for surgery would become, if we will be able to stop the flow in a major artery without exploration, external compression, and ligation…"
>
> *—Professor Nicolay Pirogov, Russian surgeon, founder of field surgery (circa 1864)*

Medicine has experienced a revolution in the use of catheter-based, endovascular techniques to manage vascular disease over the past 2 decades. In many scenarios, a less invasive endovascular approach to arterial disease or venous pathology is associated with less morbidity and lower mortality than a traditional open surgical approach.

The use of endovascular approaches for the diagnosis and management of severe injury has also increased dramatically over the past decade.[1-3] Initially limited to patterns of central vascular injury, endovascular approaches have now been shown effective in managing injury to branch and junctional vessels.[4,5] Additionally, the effectiveness of catheter-based approaches to control hemorrhage associated with solid organ injury and pelvic fracture has been refined.[6-8] Finally, there is now a renewed interest in resuscitative endovascular balloon occlusion of the aorta (REBOA) as an alternative to thoracotomy and aortic clamping for shock.[9-11]

History is replete with examples of how military experience in managing and studying a large burden of injury has advanced medicine and surgery in the civilian sector (Figure 1).[12] In this context, military surgeons have provided some of the earliest reports of endovascular approaches to vascular trauma. Decades after the foretelling statement by Russian surgeon Pirogov, military surgeons in World War I and II used hollow tubes inside of severed blood vessels as a form of intravascular repair, and Major Carl Hughes first described REBOA from a field hospital during the Korean War.[13-15]

A number of lessons from recent experiences in Afghanistan and Iraq—the first wars in which endovascular-trained providers have been deployed—shed new light on the utility of catheter-based approaches to injury.[16,17] In contrast to the medical advances for which

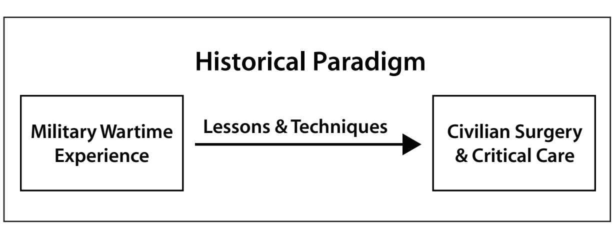


Figure 1. Schematic illustrating the historical paradigm of translation of knowledge from the military to the civilian setting.

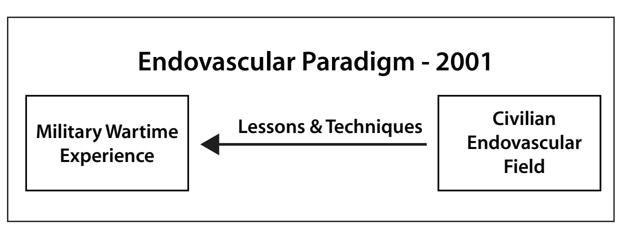


Figure 2. Schematic illustrating the translation of knowledge and devices from the civilian sector to the military during early phases of the recent wars in Afghanistan and Iraq.

the military has been the vanguard, the military has mostly benefitted in terms of endovascular therapies, receiving and implementing techniques that had been pioneered and applied in the civilian sector (Figure 2).

During the terminal phases of the wars in Afghanistan and Iraq, the military's Joint Trauma System and its Combat Casualty Care Research Program had attempted to characterize lessons learned from the use of endovascular therapies in wartime.[17] These efforts are a data-driven response built on an understanding of the timing and cause of mortality on the battlefield and the potential for endovascular intervention to mitigate shock and hemorrhage.[18,19] The military also recognizes that if endovascular technologies evolve toward the treatment of injury and shock as rapidly as they have been applied to vascular disease states, these technologies will undoubtedly play a greater role in the future management of trauma.

Guided by data showing that most combat-related deaths result from hemorrhage prior to the patient arriving to an operating room or endovascular suite, the military has proposed broader attainment of fundamental skills of vascular access and catheter-based intervention among prehospital and emergency care providers (medics, emergency physicians, and general surgeons). Additionally, the military has started to make existing and future endovascular approaches more amenable to the acute setting of trauma and shock. If aligned correctly, the military and civilian sectors can reach a more modern and productive association in which they are motivated by and benefit from each other's needs and capabilities in the endovascular arena (ie, address and innovate for both trauma and disease) (Figure 3).

The objective of this report is to characterize the relationship between civilian endovascular capability and the military's trauma care mission—past, present, and future. We aim to highlight the lessons learned from the civilian experience with endovascular technologies that have translated to military trauma care. The report also describes the lessons learned from the military's contemporary wartime experience and their influence on the future of catheter-based therapies for injury and shock.

CIVILIAN LESSONS FOR MILITARY TRAUMA CARE

Demonstration of the Utility of Endovascular Techniques

The foundation provided by the civilian vascular, trauma, and interventional communities at the start of the wars in Afghanistan and Iraq was a demonstration of improved outcomes using endovascular techniques for certain injury patterns. At that time, the military had no deployable endovascular capability and was using a doctrine stating that vascular injury was best diagnosed and managed using open surgical techniques. In a revealing 2004 publication, Gawande noted, "there is no facility or expertise in Iraq even for the routine placement of inferior vena cava filters."[20] The military's approach was understandable and largely one of practicality, given the novelty of endovascular therapies and the harsh limitations of austere wartime surgery. However, as the theaters of war became more advanced and civilian evidence continued to demonstrate the effectiveness of endovascular capabilities, the military was forced to reappraise its approach.

Soon after Gawande's article and largely as a consequence of deployment of trained endovascular surgeons, the military developed and reported on progressively more complex endovascular capability in the wartime setting.[17,21,22] Initially,

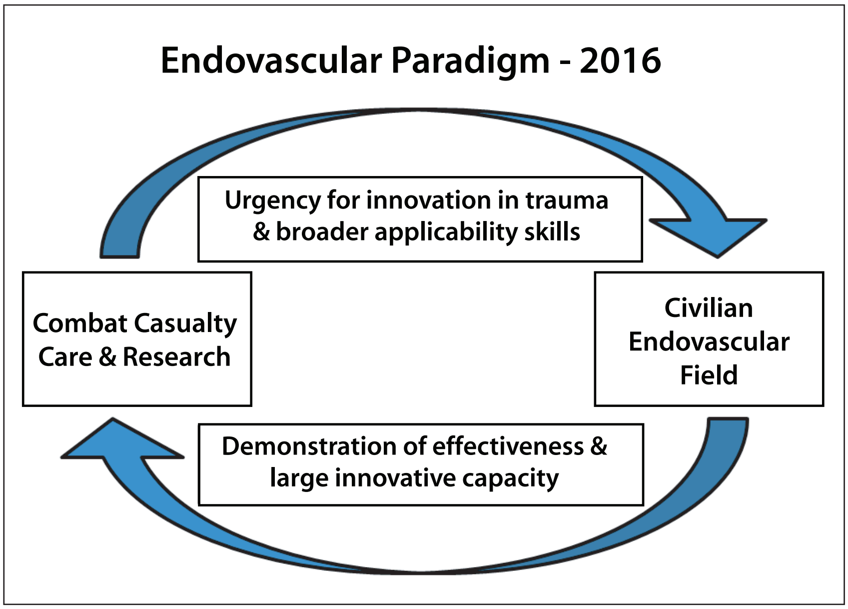


Figure 3. Schematic illustrating the potential collaboration between military trauma care and research and the civilian sector as it relates to advances in endovascular innovation.

Courtesy of Todd E. Rasmussen, MD.

Figure 4. The level III Air Force Theater Hospital on Balad Air Base, Iraq (circa 2005). In operation between 2004 and 2010, this facility was the largest and busiest Air Force Theater Hospital since the Vietnam War and the initial location where endovascular capacities to manage combat-related injury were described.

this occurred at the level III surgical facility at Balad Air Base, Iraq (Figure 4), but a similar trauma-specific endovascular capability was soon developed at the Air Force Theater Hospital at Bagram Air Field, Afghanistan. Other facilities, such as the US Navy level III facility in Kandahar, Afghanistan, followed in establishing endovascular capability, largely through efforts of forward-leaning and expert interventional radiologists. The military's integration of endovascular capability into its combat casualty care doctrine and clinical practice guidelines is far from uniform or complete. However, after demonstrating feasibility and effectiveness in austere environments, the military will need to leverage ongoing civilian experience and account for endovascular approaches (inventory, imaging, and indications) as it plans for future combat casualty care scenarios, especially scenarios in which an endovascular approach has become the accepted standard.

Modern Surgical and Endovascular Training

The civilian sector has also shown the relevance of catheter-based endovascular training. Whether in the form of fellowship-trained surgeons, radiologists, cardiologists, or other categories of providers, the civilian clinical and academic communities—many of which have trained military providers—have demonstrated the importance of programs that account for catheter-based expertise. Outside the combat zone, the vast majority of the military's endovascular specialists are engaged in managing age-related disease in the beneficiary population of the Military Health System. However, this same cadre of endovascular experts deploys to austere locations where they manage severe combat-related injury to the best of their ability. As endovascular therapies continue to improve and their effectiveness in managing certain injury scenarios becomes more established, the military and its endovascular specialists will need to prepare for catheter-based capabilities as they balance beneficiary care with readiness for state-of-the-art combat casualty care.

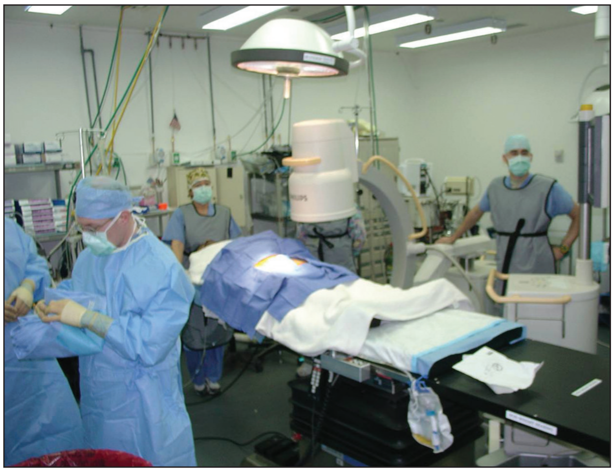
The military imperative to more effectively manage hemorrhage and shock in the prehospital and forward surgical setting is likely to challenge the traditional civilian training paradigms that limit teaching of catheter-based skills only to surgeons, radiologists, and cardiologists. In order for the military to improve its ability to save lives on future battlefields, the catheter-based skill set may need to be extended to medics, emergency medicine providers, and general surgeons.[23-25] In this context, training vascular access and basic endovascular skills—skills that may save and sustain life in the setting of hemorrhage and shock—would be formalized for those who are likely to be nearest to the hemorrhaging patient in the military operational scenario (ie, the point of injury, during en route care, and in forward surgical scenarios).[23-25]

Development and Commercialization of Endovascular Devices

The civilian sector has also provided the military with a host of vascular access and catheter-based technologies that could be utilized for certain scenarios of injury. Modern access devices such as small-caliber access needles, wires, and sheaths that facilitate safe and rapid ultrasound-guided entry into the vascular system were not included in traditional combat casualty care sets and kits. Similarly, the civilian community pioneered the use of covered stent technology (ie, stent grafts) and catheter-delivered hemostatic products (eg, coils, foams, and plugs) for managing vascular injury and bleeding from solid organ injury. Finally, compliant balloons for large vessel occlusion were pioneered by the civilian sector to be used with larger stent grafts and in managing aortic pathology. This proven technology was available to the military's deploying surgeons and was implemented in Iraq and Afghanistan. Although none of these devices has a trauma indication, and the best paradigm for a trauma-specific endovascular inventory is not defined, without civilian innovation and commercialization in the endovascular arena, the military's tool box for hemorrhage control, resuscitation, and vascular repair would have remained the same as it was at the end of the Vietnam War.

Courtesy of Todd E. Rasmussen, MD.

Figure 5. A very basic endovascular inventory of a planned case of covered stent placement across the pseudoaneurysm of a peripheral artery. Although this image is not the entirety of the inventory, it illustrates the basic nature of materials available to accomplish endovascular procedures in an austere wartime environment.



Courtesy of Todd E. Rasmussen, MD.

Figure 6. The basic endovascular arrangement for a planned procedure in the level III Air Force Theater Hospital on Bagram Air Field (circa 2010). Although the imaging machine was able to produce basic digital subtraction fluoroscopy, it did not have a modern vascular software package.

MILITARY LESSONS FOR THE CIVILIAN SECTOR

Value of Trauma-Specific Endovascular Inventory

Compelled to assemble supplies to be utilized in theaters of war, the military demonstrated the value of a trauma-specific endovascular inventory.[17] In this effort, the military showed that it was practical to have a limited inventory within trauma-relevant categories: vascular access, basic sheaths and catheters, 0.035-inch guidewires, covered stents, 0.035-inch coils, one type of compliant large-vessel occlusion balloon, and one type of removable vena cava filter (Figures 5 and 6). A comprehensive description of the inventory is beyond the scope of this report, but out of necessity, the military's inventory maintained a narrow focus. For example, the catheter-based inventory did not include angioplasty balloons, thrombolytic platforms, 0.014- or 0.018-inch guidewires, 0.014- or 0.018-inch–based devices, or bare-metal stents. Although any given case may have benefited from the availability of a more comprehensive inventory (ie, "just one more" wire, catheter, or stent), the setting in which the supplies were assembled, stored, and used necessitated efficiency.

The trauma-specific endovascular inventory for military purposes is in contrast to civilian stock rooms intended to manage many different conditions and circumstances. It should be emphasized that the military's trauma-specific endovascular inventory is not fully defined or established in doctrine at this time. However, recent experience should provide a foundation for military medical planners to ensure relevant endovascular inventories are included in future forward surgical units and theater hospitals. Finally, aspects of the military's experience in establishing a trauma-specific endovascular inventory may provide a model for civilian centers to improve efficiency in providing catheter-based capability in the trauma setting.

Feasibility of Endovascular Techniques in Acute and Austere Environments

The military has the ability to accomplish endovascular procedures in challenging circumstances using a limited inventory with limited imaging capability (Figures 7–9).[17,21] Military providers showed that catheter-based procedures can be accomplished in the acute setting using analog and digital x-ray machines, small and dated fluoroscopic units designed for orthopedic procedures, and without vascular software packages (Figure 6). Although the number and complexity of endovascular procedures performed in Iraq and Afghanistan were relatively limited, placement of covered stents, snare retrieval of missile emboli, and coil embolization of solid organ injury, pelvic fracture, and pseudoaneurysms were accomplished using rudimentary imaging devices and inventories.[17,21] This experience provides a balanced perspective in an era that demands the best imaging unit or next-generation endovascular device and provides evidence of feasibility for those undertaking basic endovascular intervention in the prehospital, emergency department, or basic trauma room setting.

Figure 7. CT image of contrast extravasation from the right lobe of a patient with a severe overall injury severity score.

Endovascular Skills for Those Closest to the Hemorrhaging Patient

For endovascular techniques to be most effective in the setting of injury and shock, providers other than endovascular surgeons and interventionists will need to attain access and catheter-based skills.[3,23-25] Patients with acute injury who are bleeding require immediate attention, whether at the point of injury, during the en route care setting, or in the emergency department. Because of the acuity of these patients, resuscitation and stabilization maneuvers must be performed quickly, often before the arrival of an endovascular specialist.

After attending to the patient's airway, care in these settings begins with vascular access (venous and arterial) and initiation of blood product infusion. In many cases, judicious use of blood products and tenets of permissive hypotension will suffice until the patient can be managed by a surgeon or interventionist (ie, definitive surgical or endovascular hemostasis). However, in patients who are "transient responders," those with prolonged prehospital times, or those in more remote locations where surgical or specialty care is not readily available, another level of basic catheter-based maneuvers may be beneficial.[23-25] The clinical need and the continued development of easier-to-use endovascular devices are likely to drive endovascular resuscitative procedures into the hands of nonsurgeons and noninterventionists as we seek to reduce potentially preventable death from bleeding.[23-25] Admittedly, this lesson will be challenging for several disciplines in the civilian and military setting to consider and accept. However, from the military's standpoint, having enhanced resuscitative capability in the hands of prehospital and emergency department providers is the only way to make progress in reducing combat-related mortality from hemorrhage in future years.[18,19]

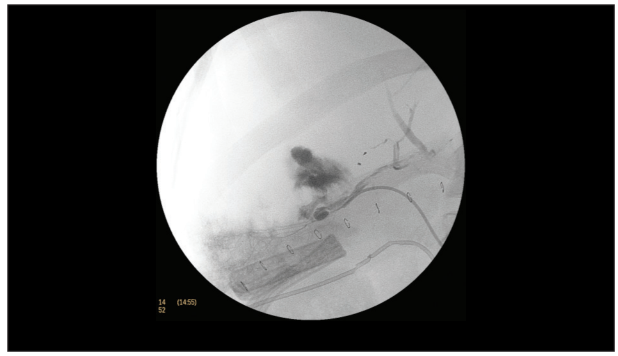


Figure 8. Hepatic arteriography demonstrating extravasation of contrast from the right hepatic artery in the same patient as in Figure 7 who had delayed bleeding several days after exploratory laparotomy and packing. A catheter-based approach to this scenario was chosen to reduce the overall morbidity of a subsequent operation to control bleeding. Note in the image the presence of a packing sponge, a drain, and skin staples indicating the previous or initial operation.

Figure 9. Hepatic arteriography demonstrating successful coil placement and control of bleeding from the branch of the right hepatic artery. The transbrachial delivery of coils to control bleeding from the liver demonstrated the facile capability that had been developed toward the later stages of the wars in Iraq and Afghanistan.

CALL FOR ENDOVASCULAR INNOVATION FOR TRAUMA

Finally, the military's trauma care and research programs have recently emphasized catheter-based innovation that can be applied to scenarios of acute injury and shock. The pace of innovation for age-related disease over the past decades has been swift and has resulted in development and refinement of approaches for cardiac and peripheral vascular disease (eg, coronary artery disease, cardiac valvular disease, and the spectrum of aortic pathology). This endovascular innovation has reduced morbidity and mortality associated with many different disease states, but it has to a relative degree neglected scenarios of trauma.

Examples of catheter-based research and device development for acute injury and shock exist, including the ER-REBOA balloon catheter (Pryor Medical Devices, Inc.), which has useful features for large vessel occlusion in the acute setting. However, the capacity for new lifesaving endovascular innovation for conditions of injury and shock appears to be much greater. The military's trauma research program has attempted to spur such innovation, including new approaches to vascular access, vascular injury repair, hemorrhage control, maintenance of cerebral perfusion, and extracorporeal organ support. Additionally, new technologies developed for managing trauma may lead to adjuncts such as automated variable aortic control, whole body or regional cooling, and catheter-directed delivery of pharmaceuticals or cellular therapies that improve survival and recovery.

CONCLUSION

Prior to and during the wars in Afghanistan and Iraq, lessons in endovascular therapies came largely from the civilian sector. As the first wars to occur during the endovascular era and the first in which endovascular specialists were deployed, the military adopted these lessons and technologies and showed that they can be used to manage certain scenarios of combat injury. In this effort, the military demonstrated efficacy and efficiency of a trauma-specific endovascular inventory. Today, evidence shows that the majority of combat-related mortality occurs from hemorrhage during the acute phases of care. To address this, it is necessary for vascular access and resuscitative endovascular skills to be attained by providers other than today's endovascular specialists.[23-25] Development of devices that are easily used in the acute setting is needed. As the military and civilian endovascular communities continue to collaborate, it will be important to continue to recognize shared experiences, priorities, and innovative capabilities (Figure 3). If developed, this partnership has the potential to catalyze innovation and practice that will improve survival and recovery of all severely injured patients. ■

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