



Damage Control Vascular Surgery

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Abstract

Purpose of Review Exsanguination is one of the most fearsome sequelae of trauma and is responsible for a large portion of both civilian and military mortality. The concept of damage control surgery is a critical development in the field of trauma largely driven by the growing understanding that coagulopathy and physiologic derangements are the primary cause of death in critically ill trauma patients. Damage control vascular surgery focuses on the rapid temporization of vascular injuries.

Recent Findings Balloon occlusion can be utilized for rapid hemorrhage control (REBOA, foley catheter, retrohepatic caval balloon, etc.). In the setting of damage control, most veins can and should be ligated. Consideration of shunting should be made regarding the suprarenal inferior vena cava, the portal vein, and the superior mesenteric vein. The named arteries should be shunted and repaired when possible; however, redundant arterial beds can be safely ligated. Vessels of all sizes can be safely shunted with commercially available or improvised devices. Systemic heparinization is not necessary to maintain patency. More recently, the concept of using endovascular stents as long-term shunts has gained attention. These can be deployed traditionally under angiographic guidance or using the novel direct site endovascular repair (DSER) technique.

Summary The rapidly evolving field of endovascular trauma management has afforded a host of new management strategies for the physiologically deranged critically ill trauma patient.

Keywords Trauma · Damage control · Vascular surgery · Endovascular · REBOA · Direct site endovascular repair

Introduction

Exsanguination remains one of the most fearsome of trauma sequelae, resulting in cardiovascular collapse, anoxia, myocardial dysfunction, and finally, death [1]. Hemorrhage is responsible for 30–40% of civilian trauma mortalities [2] and was responsible for 80% of combat mortalities occurring in patients with potentially survivable injuries over a 10-year period during the Iraq and Afghanistan conflicts [3]. Consequently, early hemorrhage control remains the central tenet and ultimate goal of trauma surgery. While precise determination of the volume of hemorrhage cannot be directly

measured in the acute phases of injury, abbreviated time to hemorrhage control—as a proxy—is known to be associated with lower morbidity and improved outcomes [2]. All efforts at early hemorrhage control are fueled by the recognition that patients with profound hemorrhage often die of their injuries before definitive vascular control has been obtained [4].

Over the past decade, improved diagnostic techniques, resuscitation protocols, and novel hemostatic agents have mitigated the risk of death due to hemorrhage. In spite of this progress, early hemorrhage control continues to be a clinical challenge. At accessible locations, tourniquets and direct pressure can temporize bleeding. An enhanced understanding of the impact of hemorrhage at noncompressible sites [3], however, has raised awareness of a need to develop and further refine existing techniques that afford rapid control of hemorrhage at these difficult to access locations.

The concept of damage control surgery is a critical development in the field of trauma management, changing the traditional thought that all repairs must be completed prior to leaving the operating room at the index case. This paradigm shift is due to the recognition that coagulopathy and physiologic derangement are the primary cause of early death in critically ill trauma patients [5]. While definitive surgical

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management of vascular injuries is the ultimate objective, definitive vascular repair can be technically demanding and time-consuming. Patients with physiologic derangements may require abbreviated, temporizing “damage control” measures, which permit stabilization. This allows for a planned subsequent intervention in a more controlled setting with a more hemodynamically and physiologically normal patient.

Aortic Occlusion

One advanced damage control maneuver is temporary aortic occlusion to support proximal perfusion. Resuscitative thoracotomy with aortic cross clamping has been performed for more than 100 years [6]. In the setting of penetrating thoracic trauma, it redistributes the patient’s blood volume to myocardium and brain while providing direct access to injured organs, allowing application of temporizing measures. With a mean survival rate of 4.5% [7], the procedure is associated with significant morbidity to patient and healthcare providers.

For injuries below the diaphragm, open aortic control can be obtained through a variety of measures. Supraceliac aortic control is obtained by retracting the left lobe of the liver to the patient’s right, while the gastrohepatic ligament is opened. The distal esophagus and stomach are retracted allowing manual compression of the aorta. To clamp the aorta at this location, the right crus of the diaphragm must be divided, a clamp can then be passed taking care to not injure posterior branches of the vagus nerve. Left-sided medial visceral rotation provides excellent access to the intra-abdominal aorta where manual or clamp occlusion can be applied.

Over the past decade, resuscitative endovascular balloon occlusion of the aorta (REBOA) has become a feasible and less invasive means of obtaining proximal aortic control in patients with uncontrolled hemorrhage below the diaphragm. The concept of using balloons for vascular control is not a new one; intra-aortic balloon occlusion was first reported in 1954 by Hughes [8]. Mattox and colleagues called for the exploration of their use in the early phases of trauma care in 1979 [9]. In a later report, Feliciano et al. more formally described the concept of employing balloon catheters to control life-threatening hemorrhage in 1990 [10]. Proximal occlusion balloons have subsequently been used for management of hemorrhage in zones I and III of the neck, face, pharynx, distal internal carotid artery, and numerous other structures utilizing Fogarty, Blakemore, Foley, and/or Penrose drains [11].

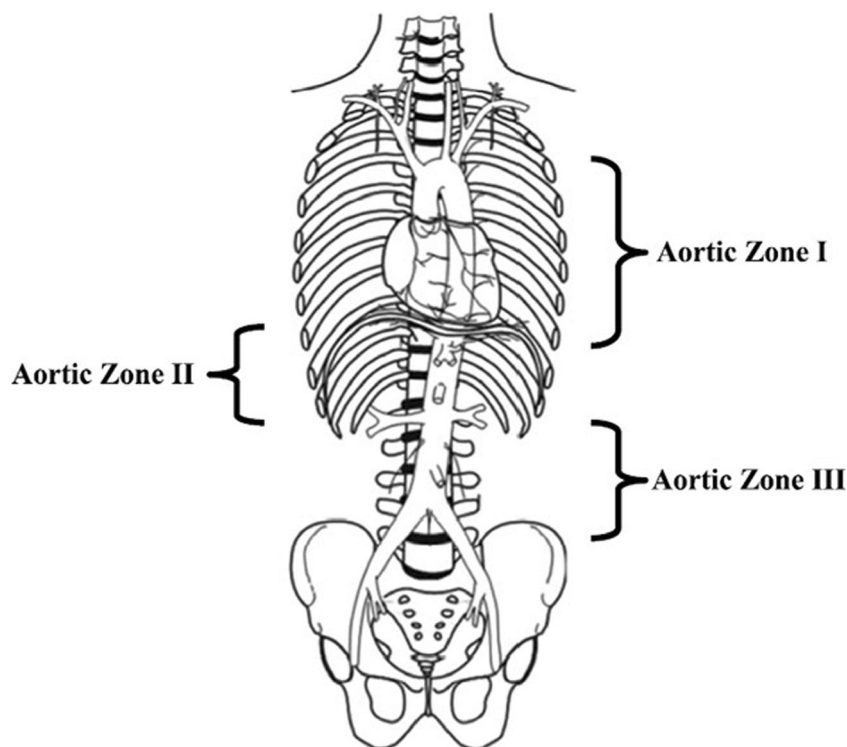
Early clinical data for REBOA has suggested improved overall survival and improved survival out of the emergency department to definitive intervention [12]. The trend toward survival to definitive intervention has been redemonstrated [13], as has the overall survival benefit [14]. Real-time videography has demonstrated that the rate-limiting step of REBOA is common femoral arterial access [15], and the

procedure can be performed in an equivalent time frame to resuscitative thoracotomy with aortic cross-clamping [16]. Indications for use of REBOA are still under investigation and are based on location of aortic occlusion. Zone I is the descending thoracic aorta between the origin of the left subclavian and celiac arteries. Zone II is a zone of non-occlusion and is comprised of the paravisceral aorta between the celiac and lowest renal artery. Zone III is the infra-renal abdominal aorta, between the lowest renal artery and the aortic bifurcation [17]. Zone I occlusion is indicated for subdiaphragmatic bleeding, while Zone III is indicated for pelvic fractures and other bleeding below the aortic bifurcation [18] (Fig. 1). For select patients, it may be performed in conjunction with high-quality CPR instead of resuscitative thoracotomy with aortic cross-clamping [12]. REBOA is able to support proximal pressure and minimize hemorrhage in a manner equivalent to resuscitative thoracotomy [19, 20].

Using presently available technology, REBOA does have some generally agreed upon contraindications. Penetrating thoracic injury in patients in cardiac arrest should be considered a contraindication for REBOA placement, as aortic occlusion at the level of the diaphragm without surgical control of hemorrhage may increase proximal pressure and rate of hemorrhage. Consequently, patients in hemorrhagic arrest or extremis following penetrating thoracic injury should undergo emergent thoracotomy if aortic occlusion is considered [21], as resuscitative thoracotomy affords both diagnosis and opportunity for immediate definitive hemorrhage control. When the thoracic cavity is exposed and proximal hemorrhage manually accessible, REBOA performed for aortic occlusion is a reasonable alternative to open cross-clamping. Severe intrathoracic vascular injury (as suggested by CXR, tube thoracostomy, or ultrasound) is also a relative contraindication for REBOA. Unstable patients with penetrating abdominopelvic or junctional injuries can be considered for zone I REBOA. Undiagnosed aortic injury, however, may preclude successful aortic occlusion [22•]. The conduct of REBOA requires adequate training in the principles and techniques involved. The critical steps of REBOA placement are arterial access, sheath placement, balloon position and inflation, management while occluded, balloon deflation, sheath removal, and post-resuscitation care. Each of these steps has unique challenges and pitfalls associated with them; consequently, the device should not be deployed without specific training.

The ideal location for arterial access is the common femoral artery below the inguinal ligament. A distal puncture in the superficial femoral artery carries a risk of arterial thrombosis and vessel occlusion due to the smaller diameter of the sheath relative to the vessel. A proximal puncture can lead to injury to the external iliac artery, which can be difficult to compress, leading to uncontrolled retroperitoneal hemorrhage. Ultrasound-guided arterial access is the standard of care in

Fig. 1 REBOA zones



elective vascular interventions, due to decreased incidence of access site complications [23, 24] and every effort should be made to utilize ultrasound in the setting of arterial access for trauma. Arterial access can be challenging in the presence of deformed anatomy, presence of a pelvic binder, or increased body mass index.

The widespread introduction of the lower profile ER-REBOA catheters specifically designed for trauma applications (Prytime Medical Devices, Inc.; Boerne, TX, USA) has been associated with mitigation of some of the risks associated with femoral access and the past requirement for larger diameter delivery sheaths required for occlusion. While newer 7 French devices require much, smaller access sheaths than the traditional compliant balloons used for aortic occlusion (12-14FR), even these smaller devices can prove occlusive in the vasoconstricted vessels of smaller trauma patients. Additionally, delivery of a sheath through a calcified vessel of an older patient, regardless of diameter size, may result in significant intimal injury.

Deployment to either zone 1 or 3 is determined based on the suspected area of injury and ideally confirmed by X-ray prior to inflation. Appropriate balloon inflation is determined by an increase in systolic blood pressure and loss of pulsatile flow distal to the balloon, which may be appreciated by loss of femoral pulse in the contralateral groin, return of proximal pulses above the level of occlusion (carotid or radial), or elevation of blood pressure above the balloon as directly measured by invasive

arterial means. While the balloon is inflated it is critical that the care team maintains a sense of urgency, as the patient remains hemodynamically unstable and still requires emergent intervention. Ischemic burden increases with longer balloon inflation times; thus, complete occlusion times after inflation for zones 1 and 3 should not exceed 30 min and 60 min respectively [25].

It is important to appreciate that, even when direct surgical control has been achieved and REBOA can be deflated, deflation of the balloon may result in an abrupt drop in afterload. This, in combination with exposure to liberated ischemic byproducts, can result in vasodilation and profound hypotension [25]. The current recommendation for deflation involves a slow, graded balloon deflation over a period of at least 5 min [18]. Both catheter and sheath should be removed as soon as possible to mitigate the occurrence of access site-related complications; including hematoma, pseudoaneurysm, arteriovenous fistula, thrombosis, embolism, and compartment syndrome.

REBOA, while a newer technology, is particularly attractive for initial management of hemorrhage at difficult to access locations, such as groin wounds and pelvic hemorrhage. While the majority of hemodynamically significant bleeding associated with unstable pelvic fractures are secondary to venous plexus disruption, transient inflow occlusion with REBOA in combination with reduction of pelvic volume with binder or external fixator may facilitate intrinsic coagulation and hemostasis, as evidenced by subsequent negative pelvic angiograms [26]. The efficacy of arterial inflow occlusion

with REBOA in the setting of abdominal venous injury has also been demonstrated in a porcine model [27].

Endoluminal balloons may also help mitigate hemorrhage in other anatomically challenging locations. Retrohepatic caval injuries are extremely lethal. Proximal and distal control is difficult to obtain due to the area of injury and the fragile wall of the vessel. While mobilization of the liver improves access, it also can increase the volume of hemorrhage, further obscuring visualization, due to loss of tamponade effect. Animal and translational research suggests that balloon occlusion of the IVC with a compliant balloon may be feasible [28, 29] and concomitant use of aortic balloon occlusion and the Pringle maneuver may better facilitate total hepatic isolation [27]. It should be noted, however, that the abrupt decrement in preload associated with balloon occlusion of the retrohepatic cava is unlikely to be well tolerated by the volume-depleted patient.

Ligation

The major named arteries should be repaired or reconstructed if possible. Ligation may be appropriate in the setting of damage control, as preservation of life supersedes preservation of limb. Areas of the body with redundant arterial supply (i.e., forearm, leg) and collateral vascular pathways are more tolerant of arterial ligation. Ligation of the carotid artery has been described without residual ischemic sequelae; however, this is predicated upon the presence of an intact Circle of Willis, which is often not known at the time of damage control intervention. Injury to the superior mesenteric artery can be quite morbid, as loss of perfusion to the small bowel is not well tolerated. Ligation of the SMA should be avoided in most instances if shunting of this vessel is a viable option [30].

Most venous injuries can be ligated in the setting of damage control; however, translational research from the military and civilian settings has suggested improved outcomes if attempts are made at venous injury repair [31]. Inferior vena cava injuries are rare [32] but are associated with a mortality rate of 66% [33]. Because this is a low-pressure system, consideration should be given to the application of gentle pressure and the use of topical hemostatic agents. Surgical access to the infrarenal IVC is obtained via right-sided medial visceral rotation. Ligation of the infra-renal IVC is typically considered an acceptable damage control approach in patients with significant physiologic derangement [34]. A known sequela of infrarenal IVC ligation is lower extremity edema and venous insufficiency. A single-institution retrospective review reported 41% early mortality associated with IVC ligation, which was 3× the mortality rate in patients who underwent repair. This disparate mortality rate and the decision to ligate are likely secondary to the patient's increased injury burden and not the result of ligation [35]. Infrarenal IVC ligation

frequently requires lower extremity fasciotomies because of the initial increase in venous hypertension resulting in compartment syndrome [36]; however, clinical data has demonstrated that not all patients with infrarenal IVC ligation will develop elevated compartment pressures [35]. Conservative management with elevation, compression, and serial compartment pressure assessment is critical.

Surgical exposure to the suprarenal inferior vena cava is obtained by performing a Kocher maneuver. Suprarenal IVC ligation may be performed, but is only rarely associated with survival. The aforementioned study had one suprarenal ligation survivor, who required a single month of hemodialysis and had no reported long-term sequelae [35]. Most other reports of suprarenal IVC ligation are in the non-trauma pediatric population, also with minimal long-term sequelae [37].

Mesenteric and portal venous injuries are rare and consequently, there is little evidence to guide best practices. These injuries are especially challenging in the face of an expanding hematoma which obscures visualization of the injury. Control with a Pringle maneuver followed by dissection of portal structures in combination with reduction of arterial inflow with REBOA or aortic cross clamping can facilitate identification of area of injury. The portal vein can be ligated after confirmation of a patent hepatic artery, this decreases the likelihood of the development of acute hepatic necrosis. Superior mesenteric vein ligation is highly morbid due to the resultant visceral ischemia; reconstruction is recommended as soon as the patient's condition permits.

Initial temporary control of iliac vein injuries can be attempted with sponge-stick compression; however, these vessels can be ligated in the setting of damage control. Post-operative elevation and compression as well as monitoring for the development of compartment syndrome are critical.

In patients in extremis with severe physiologic derangements, ligation does provide a means of preserving life; however, modern experience suggests that the liberal use of intravascular shunts is a more appropriate damage control intervention for injuries to most vessels that are amenable.

Temporary Vascular Shunts

Translational research from recent military conflicts has provided more data supporting the intuitive concept that early restoration of in-line flow and perfusion of distal tissues following vascular injury is critical [38]. The long-standing involvement in conflict in Iraq and Afghanistan has provided a wealth of data regarding shunt management for temporizing vascular injuries [39–42], and shunt use has become increasingly common in the management of civilian trauma [43–49]. The lack of premorbid peripheral vascular disease, resultant arterial collateralization, and ischemic preconditioning places

young trauma patients at elevated risk for the ischemic sequelae of abrupt cessation of arterial inflow [50, 51].

Translational studies have demonstrated a significant increase in ischemic injury with increasing time to reperfusion in the setting of antecedent hemorrhage [52]. Clinical experience from the military has reported an impressive 95.6% patency rate of proximal vascular shunts placed prior to evacuation to a higher level of care. All of these underwent successful autologous reconstruction, with an average time from injury to reconstruction of 5:48 (\pm 2:08). All survived their injuries, and there was a 100% early limb preservation rate reported [53].

Subsequently, the analysis by Gifford et al. from the Global War on Terror vascular injury initiative reported that after propensity score adjustment, the use of temporary vascular shunts was associated with a reduced risk of amputation [40]. A more recent retrospective study found no difference in amputation rates between patients with vascular injuries in whom shunts were initially placed and those who underwent definitive repair at index operation, concluding that temporary vascular shunt use is safe [39].

Endoluminal temporary shunts should be utilized in arterial injury to moderate sized vessels (i.e., popliteal, visceral arteries) and should be considered for larger venous injuries as a temporizing measure. Commercially available stents employed in elective vascular surgery are well-suited for this purpose. There are a variety of commercially available shunts. Argyle carotid artery shunts (Sherwood Medical, St Louis, Missouri, USA) are packaged in a range of sizes (8–14 FR) in a single container, making their selection a good, all-purpose improvised trauma shunt choice. In a large single-institution review, the most frequently utilized shunt for management of peripheral arterial was the 14 FR Argyle carotid artery shunt [49] (Fig. 2). Other commercially available shunts, including the Javid Carotid Bypass Shunt (17 FR, Bard Implants Division, Billerica, Massachusetts, USA) and Pruitt-Inahara Carotid Shunts (9 FR, Ideas for Medicine, St.

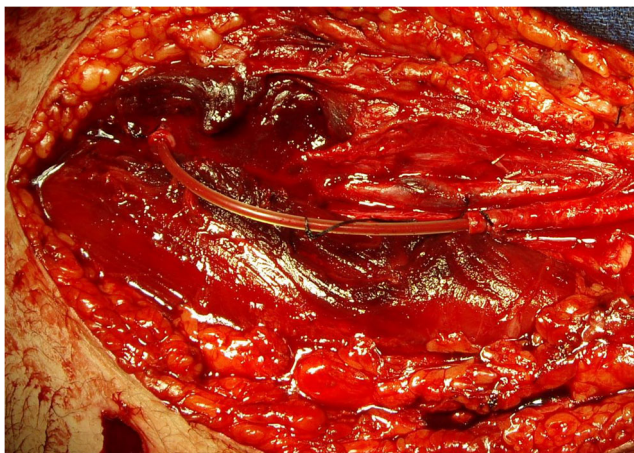


Fig. 2 Argyle shunt in superficial femoral artery

Petersburg, Florida, USA) which may prove to be more useful depending on the location and nature of the injury. For retrohepatic caval injuries, large-bore chest tubes (36–40 FR) can be utilized as atriocaval shunts. However, this requires opening a second body cavity via thoracotomy or sternotomy to access the right atrium for shunt placement. This procedure is technically very challenging and has a 20% survival rate reported in the literature [54]. Large-bore chest tubes can be similarly used for aorta and vena cava shunts; however, this may result in inadequate perfusion/drainage of branch vessels. In extreme circumstances, intravenous tubing or other soft sterile cylindrical structures (i.e., feeding tubes) can be utilized to restore perfusion for temporary durations.

In order to decrease the likelihood of shunt thrombosis, the largest shunt possible should be utilized. Careful insertion of the shunt is necessary to prevent additional vessel trauma and distal dissection. When the distal end of a transected vessel is in spasm, topical application of papaverine combined with gentle mechanical dilation may allow for insertion of a larger shunt [55]. Prior to insertion, the proximal and distal injured vessel should be debrided and confirmed to be free of thrombus, either by observation of adequate forward and back-bleeding or utilization of Fogarty embolectomy catheters. Local flushing of the vessel with heparinized saline may be useful in promoting clearance of residual clot; however, no data exists regarding the optimal dose or administration strategy. The local application of heparin is unlikely to contribute to systemic coagulopathy, but again, no data exists regarding the systemic absorption of locally administered heparin; thus, it should be used with caution in patients with concomitant brain injury or other contraindications to anticoagulation.

With isolated extremity injuries, consideration should be given to systemic anticoagulation. In the setting of nontraumatic acute limb ischemia, upon diagnosis, prompt initiation of systemic anticoagulation is considered standard of care [56, 57]. The true benefit of this practice with regard to promoting shunt or subsequent repair/graft patency is unknown. Clinical experience and animal data, however, suggest that temporary shunts of proximal extremity arterial injury will maintain patency for prolonged periods without the use of systemic anticoagulation [46].

A Rummel tourniquet (umbilical tape or silastic vessel loops), 2–0 silk ties, or inflating the balloons of the Pruitt-Inahara Shunt are used to secure the shunts and prevent dislodgement during patient movement. Care should be taken to avoid additional injury to the vessel proximal and distal to the zone of injury during shunt placement, as this will necessitate further debridement on re-exploration, thus increasing the conduit defect.

For patients in extremis, endovascular interventions can be appropriate and potentially life-saving. The PROspective Observational Vascular Injury Trial (PROOVIT) registry

demonstrated an increasing utilization of endovascular therapies in the setting of blunt trauma, specifically in patients with noncompressible torso hemorrhage. Endovascular intervention was associated with a decreased blood transfusion requirement [58•]. Endovascular repair of a peripheral vascular injury requires remote arterial access, generally in one or both common femoral arteries, upsizing a sheath to the appropriate size, and passing a wire across the site of injury. Contrast angiography is typically used prior to intervention to define anatomy, with it carries a risk of acute renal failure. A variety of peripheral-covered vascular stent grafts are available, which can be utilized for treatment of peripheral vascular injury, often sparing extensive soft tissue dissection. Self-expanding stents (Fluency, Viabahn) and balloon expandable (I cast, Jo stent) are available on the market. Traditionally it is taught that stents should not be placed across areas of extreme flexion or compression points that could result in stent fracture (i.e., CFA, popliteal artery, axilla); however, utilizing stents in this location as bridges to definitive repair is reasonable.

Direct site endovascular repair (DSER) is a novel hybrid approach to management of vascular injuries that is not reliant upon hybrid rooms or endovascular-trained providers. This is an open surgical reconstruction technique which utilizes self-expanding endovascular stents to create a suture-less vascular anastomosis [59]. This concept was built upon a similar technique used in open bypass procedures and has been shown to be both a durable and fast repair [60]. DSER has been compared with vascular shunts in a swine model, which demonstrated no difference in speed of deployment, but showed improved flow through the stent [61••]. This represents a novel damage control option for the management of peripheral vascular injury which approximates the results of endovascular repair without requiring imaging equipment or a provider skilled in endovascular intervention.

Most early in-hospital deaths in trauma patients are secondary to hemorrhage and occur at a median of 2.6 h from admission [62]. As the time to hemorrhage control is a critical determinant of survival, times to endovascular intervention, which vary greatly [63, 64], should be of particular concern. Disparate time to hemorrhage control by catheter-based intervention has been reported in trauma patients presenting during vs outside normal business hours, due to the need to activate a dedicated physician and treatment team [65]. The development of a dedicated endovascular trauma service has recently been shown to decrease time to hemostasis for trauma patients requiring percutaneous intervention [66••].

Conclusion

Exsanguinating hemorrhage is responsible for a large percentage of both civilian and military trauma mortality. Growing

recognition that the physiologic perturbations associated with severe trauma are directly related to mortality rate has resulted in the near-uniform adoption of damage control approaches for the management of traumatic vascular and nonvascular injuries.

Compliance with Ethical Standards

Conflict of Interest Dr. Romagnoli has nothing to disclose. Dr. DuBose has nothing to disclose. Dr. Brenner's institution received a Department of Defense grant which ended in 2017. Dr. Brenner is a member of the clinical advisory board at Prytime Medical and receives stock options. She has nothing further to disclose.

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

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