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REBOA in Combat Casualties: The Past, Present, and Future

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Abstract

Non-compressible torso hemorrhage is a leading cause of preventable death on the battlefield. Intra-aortic balloon occlusion was first used in combat in the 1950s, but military use was rare prior to Operation Iraqi Freedom and Operation Enduring Freedom. During these wars, the combination of an increasing number of deployed vascular surgeons and a significant rise in deaths from hemorrhage resulted in novel adaptations of resuscitative endovascular balloon occlusion of the aorta (REBOA) technology, increasing its potential application in combat. We describe the background of REBOA development in response to a need for minimally invasive intervention for hemorrhage control and provide a detailed review of all published cases (n=47) of REBOA use for combat casualties. The current limitations of REBOA are described, including distal ischemia and reperfusion injury, as well as ongoing research efforts to adapt REBOA for prolonged use in the austere setting.

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REBOA; Resuscitative endovascular balloon occlusion of the aorta; austere environments

INTRODUCTION

Uncontrolled hemorrhage is the leading cause of death in combat, with most of these deaths occurring prior to definitive care(1). The use of resuscitative endovascular balloon occlusion of the aorta (REBOA) for hemorrhage control was first introduced in the combat setting in the 1950s(2). A gap analysis of injured combat casualties found that 18.5% could have potentially benefited from REBOA(3). Evolution of endovascular technology has facilitated the use of REBOA in forward deployed settings(4). However, REBOA in its current state is limited in duration by the distal ischemia it induces(5) and the reperfusion injury that results following balloon deflation(5). This time limitation hinders its utility in a prolonged field care environment. Both civilian and Department of Defense (DoD) funded researchers are actively investigating ways to overcome these challenges and enhance the practicality of REBOA in the austere setting. In this narrative review, we describe the history of REBOA, its use in recent conflicts, and ongoing efforts to improve its feasibility for future combat applications.

1. HISTORY OF ENDOVASCULAR HEMORRHAGE CONTROL AND THE RISE OF REBOA IN COMBAT

1.1 Rise of Endovascular Hemorrhage Control—The first reported use of an intra-abdominal aortic balloon occlusion (IABO) catheter for traumatic hemorrhage in a combat casualty was by Lieutenant Colonel (LTC) Carl Hughes in 1954(2). He described the use of an intra-aortic balloon occlusion catheter inserted through a 10 French arterial sheath in two gravely wounded casualties, one with extensive blast injuries from a grenade and one who had suffered multiple gunshot wounds to the chest and abdomen. In the former case, despite multiple serial balloon inflations to control bleeding concurrent with massive transfusion, the patient ultimately died on the operating room table. In the second case, the patient was peri-arrest at the time of balloon insertion, and no hemodynamic improvement resulted with balloon inflation; on laparotomy the patient was found to have exsanguinated from an iliac vein injury. LTC Hughes hypothesized that had IABO been performed sooner in these patients, they may have survived.

In the decades that followed reported uses of IABO for hemorrhage control were relegated to the treatment of ruptured abdominal aortic aneurysms (AAAs)(6). As reports of endovascular interventions for hemorrhage control in AAAs rose, there was a rising interest in the applicability of endovascular hemorrhage control devices in trauma care. In the 1980s the use of IABO for traumatic hemorrhage resurfaced in a case series of 21 injured patients cared for at the Trauma Center for Brooklyn(7). All seven surviving patients had measurable blood pressures pre-IABO; there were no survivors among patients who presented with an unobtainable blood pressure.

1.2 Development of a Novel Bedside IABO Device—Alongside these advances in endovascular care for AAAs and civilian trauma patients, the landscape of combat operations shifted. One in five combat casualties from Operation Iraqi Freedom (2003–2011) and Operation Enduring Freedom (2001–2014) suffered injuries resulting in hemorrhage (20%), and one in six had vascular trauma (12%), much higher rates than previous wars(8). However, vascular surgeons are a scarcity in the deployed setting(9), and with low vascular surgery case requirements for graduating general surgeons, there was a need to develop basic endovascular interventions for hemorrhage control which could be mastered by the surgeons who would be treating the majority of combat casualties.

The development of the REBOA catheter was driven by an urgent military need for innovative technology to reduce loss of life from hemorrhage. As the leading cause of death in combat casualties is non-compressible torso hemorrhage(1, 10, 11), the relevance of this emerging minimally invasive and portable technology was paramount. In the decades since LTC Hughes had described the first attempted uses of IABO for injuries sustained on the battlefield, several paradigm shifts had occurred which helped bring this technology closer to reality; namely, the endovascular revolution and the deployment of trained vascular and endovascular surgeons in the Iraq and Afghanistan Wars(12, 13). The first series of endovascular approaches to injuries sustained on the battlefield was described by Rasmussen *et al* in 2008, highlighting the feasibility of bringing these treatments to forward levels of care(14).

The development of REBOA was launched on several fronts as part of a military-civilian partnership(15). Military vascular surgeons, in Stannard *et al* in 2011, described REBOA as a temporizing intervention for hemorrhagic shock. They included a detailed technical description of the placement and use of IABO. Animal models of traumatic hemorrhage demonstrated the feasibility and efficacy of REBOA in reducing blood loss and prolonging survival, and the intervention transitioned from the bench to the bedside(16–19). As the focus turned to clinical applications, training courses were developed, including Endovascular Skills for Trauma and Resuscitative Surgery (ESTARS)(20), precursor to the American College of Surgeons Basic Endovascular Skills for Trauma (BEST) course. A major limitation of the application of REBOA for hemorrhage control in the austere environment of the battlefield was the large 14 French introducer sheaths initially required, necessitating surgical arteriotomy repair. Efforts focused on devising smaller devices inserted through 7–8 French arterial sheaths, without fluoroscopy to facilitate use in a resource-limited setting(21).

1.3 Modern Reports of REBOA Use in Austere Environments—In 2013, the first case series of REBOA use in six civilian trauma patients was published, with none succumbing to death from hemorrhage(22). Reports of REBOA use in civilian trauma accumulated in the following years(23, 24). The ER-REBOA™ balloon (Prytime Medical, Boerne, TX) in 2013, designed by United States Air Force vascular surgeons, led to broader adoption of REBOA(25). Inserted percutaneously through a 7 French sheath without a guidewire, the technology facilitated use by non-vascular general and trauma surgeons and could potentially be used in the far-forward environment. Compared to the prior CODA balloon (Cook Medical), which required a 14 French introducer sheath and surgical

arteriotomy repair, this lower-profile balloon saved time and decreased the morbidity of the procedure, allowing for its potential use in the far-forward environment.

The first modern published report of REBOA use in combat casualties was in 2017 (Table 1), in a case series of four wounded combat casualties by Manley *et al*(26). Three patients underwent Zone 1 REBOA placement (supraceliac thoracic aorta) and one underwent Zone 3 REBOA placement (infrarenal abdominal aorta); all survived to the next echelon of care. Long-term follow-up data are missing for many patients due to the logistical challenges of following a patient's outcomes as they transfer to local national hospitals or are repatriated to their home countries.

A total of eleven papers have been published to date describing the use of REBOA in 47 combat casualties. The majority have been from US-based forces (n=33, 70.2%), followed by eight from the United Kingdom (17.0%), and three each from Russia and Belgium (6.4% each). The largest case series is by Northern *et al* reporting on the use of REBOA in 20 combat casualties over an 18-month period. REBOA was successfully deployed in 19 of these patients, with balloon rupture noted in the one patient with unsuccessful REBOA use(27). There were no immediate fatalities in this series, nor were there any access-site complications. The patient who experienced balloon rupture underwent rapid laparotomy to evaluate for aortic injury from the balloon malfunction. None was found, and the patient survived to the next level of care. There have also been reports of REBOA use to simultaneously manage two patients requiring advanced hemorrhage control managed by the US Air Force Special Operations Surgical Team (SOST)(28). A case series from the United Kingdom similarly described the use of REBOA when immediate surgical intervention was not possible due to simultaneous casualties. Although most papers report on the use of REBOA in far-forward field hospitals, there was one published use of REBOA to maintain cerebral perfusion on a rotary wing platform while transferring a patient with a severe penetrating head injury to a higher level of care.

1.4 Injury Details—The two most common mechanisms of injury were blast injury from improvised explosive device (IED) or grenades (n=20, 42.6%), followed by gunshot wounds (GSW, n=16, 34.0%). REBOA was most commonly used for controlling truncal hemorrhage. All but two patients had intra-abdominal injuries. Abdominopelvic vascular injuries were found in more than half of these patients (n=26, 55.3%), (Table 2). Intestinal injuries were present in 17 patients (36.2%), and solid organ injuries in 13 patients (27.7%). Six patients had pelvic fractures or pelvic hemorrhage (12.8%). Most patients with interventions reported underwent laparotomy (n=36/39, 92.3%; 8 not reported).

Estimated blood loss was quantified in only five cases, (range 1.5–6L), with unquantified massive blood loss reported in several patients. Transfusion volumes ranged from 2–183 units, with a median of 10 units of blood per patient. Three patients received 157, 167, and 183 units of blood, respectively, with the remainder receiving less than 24 units of blood each. Notably, the three patients receiving the largest volume transfusions all survived.

1.5 REBOA Placement Details—REBOA was placed by a trained physician in all cases that mentioned the profession of the proceduralist. Half were placed by surgeons

(n=25, 53.2%) and nine by emergency medicine physicians (19.1%). Half were placed percutaneously (26/47, 55.3%). Most were placed via 7 French arterial sheaths (n=31), with two 8 French sheaths, and five 10 French sheaths (9 patients with sheath size not described). Time needed for arterial access was described in eight patients, ranging from 1–9 minutes. The majority were placed in Zone 1 in the supraceliac thoracic aorta (n=41, 87.2%), with the remainder placed in Zone 3 in the infrarenal abdominal aorta (n=6, 12.8%). In only one case was the balloon placement able to be confirmed prior to inflation via X-ray(35). Most patients underwent complete REBOA (cREBOA) (n=29, 61.7%). Three patients underwent cREBOA followed by partial REBOA (pREBOA) and three underwent intermittent REBOA (iREBOA). Eight patients did not have degree of occlusion specified. Duration of aortic occlusion was reported in 37 patients (78.7%), with a median total duration of 26 minutes (interquartile range, IQR 20–32; range 7–110 minutes). This is in line with current recommendations from the Joint Trauma System Clinical Practice Guideline on REBOA for Hemorrhagic Shock, which recommend limiting the duration of aortic occlusion to 15–30 minutes(36).

1.6 Response to REBOA—The median pre-REBOA systolic blood pressure (SBP) was 68.5 mmHg (IQR 58.8–80 mmHg) among 29 patients who had this information reported (61.7%), and the median post-REBOA SBP was 120 mmHg (IQR 110–122.5) among 32 patients with this information available (68.1%) ($p < 0.0001$). Of the 22 patients who had measurable and reported pre- and post-REBOA SBPs, the median increase in SBP was 51 mmHg (IQR 43.3–67.5 mmHg). Pre-REBOA SBP was reported to be non-measurable in 7 patients (14.9%), with all but one patient responding to balloon inflation with a median post-REBOA SBP of 115 mmHg (IQR 80–120). The pre-REBOA SBP was not provided in 12 patients (25.5%). Only two patients were reported to have required cardiopulmonary resuscitation prior to REBOA placement; one, a patient with an ultimately non-survivable traumatic brain injury(32) and the other, a patient with a severe unstable pelvic fracture(35). Both of these patients died. In total, four patients died (8.5%), three at the index procedure and one at a Role IV hospital due to withdrawal of support for a non-survivable brain injury. No further mortalities were reported, but follow-up data was scarce. These outcomes support the earlier assessment by LTC Hughes – that earlier access, prior to exsanguination and cardiac arrest, may represent the best opportunity for REBOA to salvage bleeding patients in extremis(2). This conclusion has also been confirmed among a larger population of civilian patients in recent years(37).

Of the 25 patients who underwent percutaneous access and survived, the majority had manual pressure applied to the access site following sheath removal (n=19). One of these patients was found to have a femoral sheath hematoma on ultrasound so the arteriotomy was subsequently repaired. Three patients had reported femoral arteriotomy repairs, and two patients had femoral sheath fascial sutures placed at the conclusion of the case without formal arteriotomy repairs(35).

Follow-up vascular imaging was reported in 28 patients out of the 43 who survived the index procedure (65.1%). This was most commonly by access-site ultrasound (n=25). Three patients underwent completion angiogram. One patient did not have any follow-up access-site imaging reported at the end of the index operation, but subsequently required a repeat

REBOA placement on the same side as the initial REBOA due to repeat hemorrhage and developed a thrombus in the popliteal artery identified on completion angiogram.

Of the 43 surviving patients, seven had REBOA-related complications (16.3%). Four patients developed thrombosis or distal embolism, with two subsequently requiring below-the-knee amputations. One patient developed a femoral sheath hematoma requiring arteriotomy repair. One patient had unsuccessful REBOA placement due to balloon rupture without arterial injury. Lastly, one patient developed acute renal failure requiring dialysis.

2. GOLDEN HOUR TO PROLONGED FIELD CARE AND THE FUTURE OF REBOA

Use of REBOA in austere environments is described in the 2020 Joint Trauma System Clinical Practice Guideline(36). REBOA in these circumstances is recommended if the patient would otherwise die within 30 minutes, a physician experienced in REBOA placement is present, blood product resuscitation is failing to resuscitate the patient, and time to definitive hemorrhage control is short. These recommendations reflect the previous Golden Hour model of the military health system in which combat injured patients were rapidly evacuated to a higher echelon of care. However, over the past decade, Gray Zone (hybrid) conflicts without a centralized conventional military force have increased, and will likely continue to do so in the future(38). This model of conflict prohibits forward staging of medical support due to the wide geographic spread of small teams. As a result, the paradigm of military medical care is shifting away from the Golden Hour model towards prolonged field care(38, 39). This shift will result in a significantly longer duration of time before injured service members reach definitive surgical care. Prolonged field care situations necessitate that hemorrhage potentially be controlled for hours. Therefore, research is ongoing to strategize methods to prolong the safe duration of REBOA use in an austere setting with limited providers and resources.

3. INCREASING SAFE DURATION OF REBOA

In animal models, periods of aortic occlusion longer than 20–40 minutes are associated with severe physiologic derangements and non-reversible end organ ischemic injury(5, 17, 40–43). Several approaches are being investigated to overcome these negative effects of prolonged REBOA use. The most developed areas of investigation are modifications of the REBOA technique designed to provide a low level of distal blood flow. Intermittent REBOA (iREBOA) is performed by periodically deflating the aortic occlusion balloon to allow for brief periods of distal perfusion. Partial REBOA (pREBOA) refers to the technique of permitting continuous, low-level distal blood flow following a brief period of initial complete occlusion. A useful description of related terminology and the distinguishing features of these and other techniques is provided by Williams et. al.(44).

3.1 Intermittent REBOA—

Intermittent REBOA (iREBOA) aims to minimize ischemia distal to the area of occlusion by intermittent balloon deflation and re-inflation after initial hemorrhage control(45). Translational work has evaluated iREBOA in swine models of hemorrhage and attempted to identify optimal schedules for balloon inflation and deflation(17, 45, 46). A time-based schedule, with deflation for 3 minutes after 10 minutes of inflation, and a pressure-based schedule, with deflation until the MAP is consistently

below a predetermined threshold, have both been evaluated in vascular injury and high-grade liver injury models with mixed results(17, 45, 46). While both REBOA deflation schedules consistently performed better than complete and continuous REBOA, neither schedule was uniformly superior to the other.

Intermittent REBOA has been used in clinical practice in Japan for trauma patients, with reported techniques of inflating the balloon for 20 minutes, then deflating with rapid infusion of blood products, and reinflation of the balloon if the proximal systolic blood pressure dropped below 70 mmHg(47, 48). Reports of use of iREBOA in combat in humans are limited to case reports and case series. While some case reports have demonstrated success with iREBOA(34), others have reported hemodynamic collapse associated with balloon deflation(2, 35).

An advantage of iREBOA is that commercially available ER-REBOA™ devices can be used for this technique. However, there are some drawbacks. The repeated acute rise in afterload created at each inflation of the balloon may be detrimental, particularly for patients with preexisting cardiac disease(45), and rapid intermittent balloon deflation may result in profound hypotension, exacerbating concomitant traumatic brain injuries(49). Notably, in non-trauma clinical use of iREBOA, prolonged total occlusion time is associated with post-operative pulmonary complications(50). Thus, while promising, iREBOA must still be used with caution(36).

3.2 Partial REBOA—Partial REBOA (pREBOA) is a novel application of REBOA that allows for low-volume flow distal to the site of the REBOA balloon(51). Ideally, pREBOA can capitalize on the improved perfusion proximal to the level of aortic occlusion, while also allowing sufficient flow past the balloon to achieve permissive regional hypoperfusion to areas of hemorrhage while lessening distal ischemia. This strategy aims to minimize ongoing hemorrhage without inducing complete distal ischemia.

Translational work has evaluated pREBOA in swine models of controlled hemorrhage, uncontrolled hemorrhage and controlled hemorrhage followed by uncontrolled hemorrhage(52). As pREBOA is in development, there is no defined criteria for what constitutes pREBOA, or how the degree of pREBOA should be measured. Studies have used distal to proximal pressure gradient(51, 53), distal flow(54), and targeted proximal systolic blood pressure(55) to define pREBOA. Most groups have included an initial 10–15 minutes of complete aortic occlusion prior to pREBOA with the theoretical intent of allowing for clot stabilization(51, 53, 54, 56–58). These studies have shown advantages of pREBOA over cREBOA, including improved survival, reduced distal ischemia, and reduced resuscitation requirements(53, 55, 58, 59). Critical for a prolonged field care scenario, pREBOA has also been demonstrated to allow for longer periods of occlusion, with studies demonstrating survival with up to two hours of pREBOA(54, 60). When compared to iREBOA, pREBOA has been demonstrated to be associated with fewer precipitous drops in mean arterial pressure (MAP), suggesting a potential benefit of improved hemodynamic stability(61).

Clinical reports of the use of pREBOA are limited, and mostly use the ER-REBOA™ balloon, which was not designed for flow titration. The largest reports have come from Japan

and are retrospective(62–64). They have reported an association between use of pREBOA and higher rates of hemodynamic improvement and stability. However, it is not possible to directly link the use of pREBOA to these positive outcomes given the retrospective nature of the reports. Other reports of clinical pREBOA use for trauma are limited to case series and case reports(30, 65–67). Military uses of pREBOA have been reported by the Belgian Special Operations team in three patients using the ER-REBOA™ catheter, with all patients surviving to evacuation after approximately 30 minutes of pREBOA(30).

3.3 Novel Catheters—A significant challenge posed by the use of pREBOA is accurate determination of the degree of aortic occlusion and of distal perfusion. As mentioned, the ER-REBOA™ catheter, the most commonly used REBOA catheter, was not designed to allow for partial distal perfusion, or for titration to a specific blood flow past the catheter, nor were other commercially available catheters. Evaluation of the ER-REBOA™ catheter in animal models has demonstrated that minimal balloon deflation results in a rapid increase in aortic flow, and the required reduction in volume of the balloon to allow for distal flow varied significantly between animals(68).

Given this clinical need, multiple catheters for titration of distal flow have been investigated. These include the bilobed pREBOA catheter (Prytime Medical, Boerne, TX) and the pREBOA-pro catheter (Prytime Medical, Boerne, TX). The bilobed pREBOA catheter has a large compliant balloon and a smaller noncompliant balloon. The smaller balloon stents out the aortic wall and allows for some degree of flow in channels between the smaller balloon, the larger balloon, and the aortic wall(56). This has been demonstrated to allow for accurate titration of flow in an animal model, with a consistent relationship between percentage of maximal balloon inflation and distal flow, and requires fewer titrations than the ER-REBOA™ to achieve a target distal MAP(54, 69). The pREBOA-pro catheter features a semi-compliant balloon that contains flow channels. When the balloon is partially inflated, the flow channels allow for blood flow while the balloon's outer circumference stays in contact with the aortic wall. When the balloon is fully inflated the flow channels close, resulting in complete aortic occlusion(70). Compared to the bilobed pREBOA catheter, the pREBOA-pro catheter allows for easier targeting of distal flow(70). Other balloon designs have been tested in preliminary animal studies, but only one, the pREBOA-pro has been approved by the FDA(71). The pREBOA-pro catheter is the first commercially available pressure regulated balloon designed to achieve partial aortic occlusion. It remains to be seen if its clinical use will achieve the extended periods of occlusion described in translational reports.

4. ENHANCING ISCHEMIA TOLERANCE

Utilization of iREBOA and pREBOA can decrease the ischemic injury associated with aortic occlusion. However, given the potential for prolonged periods prior to definitive care, supportive therapy in the form of medications that enhance ischemic tolerance have the potential to increase survival in wounded soldiers(72).

4.1 Valproic Acid—Valproic acid and other histone deacetylase inhibitors have been studied in the treatment of hemorrhagic shock and ischemia-reperfusion injuries(73).

Valproic acid enhances cellular ischemia tolerance and improves survival of un-resuscitated swine in hemorrhagic shock similarly to whole blood transfusion(74). The proposed mechanism of valproic acid is through post-translational protein modifications that upregulate genes associated with cell survival, proliferation and differentiation, and downregulate genes associated with cell death and inflammation(75, 76). Valproic acid has been demonstrated to improve survival in a 50% hemorrhage swine model(77). In a hemorrhage and ischemia-reperfusion model valproic acid decreased acidosis, coagulopathy, ischemic liver injury, and pathological overexpression of various genes relative to animals receiving fluid resuscitation alone(78, 79). Prior to translation to use in humans, the optimal dose must be identified. Phase 1 trials have demonstrated the maximum tolerated dose in healthy human subjects to be 140 mg/kg(80). There are on-going studies evaluating whether or not the addition of valproic acid to pREBOA can further extend occlusion time or potentially reduce its morbidity.

4.2 Hypothermia—The greatest ischemic burden with Zone 1 REBOA is on visceral organs and much work in evaluating pREBOA and iREBOA has been done to decrease this ischemia, however distal skeletal muscle ischemia is also a concern. While Zone 3 REBOA avoids the risks of visceral organ ischemia, perfusion to the lower extremities remains compromised. Skeletal muscle ischemia can cause irreversible neuromuscular damage at less than three hours(81, 82). Hypothermia has previously been used to preserve organ function for transplant and after cardiac arrest. In an austere environment, hypothermia could allow for prolonged ischemia while awaiting transport to definitive care. Hypothermia achieved by external cooling has been demonstrated to decrease skeletal muscle ischemia after four hours of Zone 3 complete REBOA(83). However, this benefit appears to be time limited, with no improvement when animals were cooled while undergoing 8 hours of REBOA(84). The ultimate impact of hypothermia on a human patient who has not yet undergone definitive surgical management remains to be seen, and risks of hypothermia associated coagulopathy require further investigation. Additionally, transport of cooling blankets and ice packs may limit the locations in which this technique can be applied.

5. NOVEL TECHNOLOGY TO FACILITATE REBOA USE IN THE AUSTERE ENVIRONMENT

5.1 Decreasing the Need for Constant Balloon Adjustment—Maintaining distal perfusion or flow at a set rate using pREBOA requires constant balloon adjustment, even with novel catheters(69, 70). This may be challenging in a battlefield situation with limited providers. An automated variable aortic control circuit could be beneficial in decreasing the need for a provider to perform frequent flow adjustments. Williams *et al* first described a hybrid endovascular-extracorporeal circuit variable aortic control (EVAC) device in 2016(85). A commercially available flow monitor, a novel extracorporeal flow catheter and a custom designed control system were combined to develop an automated system of extracorporeal blood flow control with concomitant bi-cannulation of the carotid and femoral arteries, allowing for carotid pressure-dependent extracorporeal flow of oxygenated blood distal to a Zone 1 REBOA balloon. As a proof of concept, this circuit was able to maintain a proximal MAP of >60 mmHg in animals with a liver injury during 70 minutes of REBOA with adjustments in flow based on proximal MAP(85). Building on this idea, other iterations provide computer-controlled, dynamic IABO balloon adjustment in response to

changes in the patient's vital signs without the need for extra-corporeal circuits or additional cannulation sites(86). In an austere environment where there are limited providers, an automated device could allow for hemorrhage control via REBOA while freeing up a provider for other pressing needs. This could prove critical in a situation with multiple casualties or in a patient with polytrauma requiring multiple interventions.

5.2 Improving Arterial Access and Balloon Positioning—Use of REBOA in the austere environment is also challenged by limited imaging capabilities. Ultrasound is a portable imaging modality that may be used to facilitate multiple steps in the process of REBOA placement. Ultrasound may facilitate percutaneous common femoral artery (CFA) access, avoiding the need for a femoral artery cut-down. A cut-down is more morbid and requires closure of the arteriotomy, as opposed to percutaneous access, which typically only requires manual pressure over the access site at the conclusion of the procedure. In particular, the development of lower-caliber femoral sheaths, such as the 7 French sheath used in the majority of cases included here, has greatly reduced the need for arteriotomy closure. However, a surgical cut-down remains a viable option, in particular among patients in extremis, and has been shown to be associated with shorter time to aortic occlusion than percutaneous access(87).

Arterial access remains the rate limiting step in REBOA placement and earlier arterial access decreases time to hemorrhage control(88). In the far forward austere environment, access to ultrasound may be limited. Devices have recently been investigated to overcome some of the limitations of traditional vascular access devices. Franklin et al. have designed a handheld multi-needle device that allows a provider to simultaneously advance three access needles, and then to cannulate through the needle that aspirates blood, potentially allowing for more rapid vascular access(89).

Other products are in development to increase the safety of vascular catheterization in settings with limited resources for imaging confirmation. Avneri et al. have designed a vascular access device that would advance a guidewire though a needle when pressure sensors in the needle indicate that the tip is in an artery(90). Pressure coupled needles are also in development, that would allow for easy identification of placement of the needle tip in an artery(91). After needle placement, devices are also being developed to ensure the catheter tip remains in the vessel and the REBOA balloon is inflated in the correct location. One device in development involves a catheter guiding tip that can be initially compressed to allow for insertion through a sheath, but once in the vessel, expands and is resistant to compression, reducing the potential for the device to unintentionally divert into a smaller branch vessel(92). An alternative device includes a magnetic catheter tip localization method. Magnetic field detectors can be placed on top of the patient's body and indicate when the catheter tip is passing below them. This could both demonstrate passage of the catheter tip in the appropriate direction, and confirm aortic zone prior to inflation(90). While these are not yet commercially available, increasing the ease and safety with which vascular access can be obtained has the potential to decrease the time to balloon inflation and expand the resource-limited environments in which REBOA can be used.

Once the artery has been accessed, assessing appropriate balloon placement and whether the aorta has been fully occluded can be challenging in an austere environment without access to fluoroscopy. Pulse exams during transport or chaotic combat environments may be unreliable. Methods under investigation for accurate balloon placement include modified catheters with collapsible, self-centering wire systems(21), and magnetically trackable balloons(93). Ensuring full aortic occlusion and accurate balloon placement has been successfully addressed in animal models with a handheld infrared imaging device(94, 95).

6. PROVIDER TRAINING

Utilizing REBOA in the resuscitation of a severely injured trauma patient is a team sport, and both surgeons and emergency physicians who may be deployed to the austere environment must be trained in the placement, use, and monitoring of REBOA in severely injured patients(96). Even more far-forward, efforts have been made to train non-physicians, including military medical technicians and nurses who may have earlier access to combat casualties, and have been successful(97, 98). Low-cost REBOA trainers have been developed which could improve access to training resources in the austere setting(99). Deterioration of skills may be seen with lack of exposure, however, and repeat training may be needed at 6-month intervals(100). REBOA has been added as a skill included in the new Advanced Surgical Skills for Exposure in Trauma (ASSET) beta course, designed to train military members in essential trauma skills before deployment.

CONCLUSION

Use of REBOA in combat trauma care has evolved significantly in the past decade. While REBOA is increasingly being successfully utilized to prevent death from hemorrhage in combat casualties, ongoing research has the potential to broaden the applicability of REBOA in austere combat environments. Further animal and human studies on adjuncts that reduce ischemic injury could facilitate longer aortic occlusion times allowing for transport of injured patients. Novel technology that facilitates rapid and easy vascular access may reduce time to REBOA inflation and broaden the spectrum of providers who can place a REBOA. These efforts may change the face of combat casualty care, with great potential to limit the loss of life due to non-compressible torso hemorrhage.

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Table 1:

Publications reporting REBOA use in combat casualty care.

Paper	Year	# patients	Country	Femoral access	REBOA provider	REBOA Zone	Mortality (%)
Hughes(2)	1954	2	US	Cut-down	NS	Zone 1	100
Glaser(29)	2017	1	US	Cut-down	Surgeon	Zone 1	0
Manley(26)	2017	4	US	Perc	Surgeon (n=2), EM (n=2)	Zone 1 (n=3) Zone 3 (n=1)	0
Manley(28)	2018	2	US	Perc	Surgeon (n=1), EM (n=1)	Zone 1	0
de Schouetheete(30)	2018	3	Belgium	Perc (n=1), Cut-down (n=2)	Surgeon	Zone 1	0
Northern(27)	2018	20	US	Perc (n=14), Cut-down (n=6)	Surgeon (n=14), EM (n=6)	Zone 1 (n=17) Zone 3 (n=3)	0
Campbell(31)	2019	8	UK	Cutdown	NS	Zone 1	NS
Brown(32)	2020	1	US	Perc	NS	Zone 1	100
Knipp(33)	2020	2	US	Perc	Surgeon	Zone 1 (n=1) Zone 3 (n=1)	0
Lewis(34)	2020	1	US	Perc	NS	Zone 3	
Reva(35)	2020	3	Russia	Perc (n=2), Cut-down (n=1)	Surgeon (n=2), NS (n=1)	Zone 1	33%

REBOA: Resuscitative Endovascular Balloon Occlusion of the Aorta; Perc: percutaneous; NS: not stated; EM: Emergency Medicine; US: United States; UK: United Kingdom.

Table 2:

Injuries sustained by combat casualties undergoing REBOA placement. Note: injury subtypes may add up to more than the total number for each injury group as many patients suffered multiple injuries.

Injury	Number of patients
Intra-abdominal vascular injury	**26**
Mesenteric vessels	19
Iliac veins	4
Iliac arteries	2
Renal artery	1
Gastric vessels	1
Inferior vena cava	1
Bowel injury	**17**
Solid organ injury	**13**
Liver	7
Spleen	6
Kidney	2
Other organs	**5**
Bladder	4
Pancreas	1
Pelvic fractures or hemorrhage	**6**
Lower extremity injuries	**5**
Vascular injury	2
Mangled extremity	1
Traumatic amputation	1
Injury not specified	1
Penetrating brain injuy	**1**