Received: 3 February 2022 | Revised: 14 March 2022 | Accepted: 21 March 2022

DOI: 10.1111/trf.16961

REVIEW

TRANSFUSION

A review of two emerging technologies for pre-hospital treatment of non-compressible abdominal hemorrhage

Brendan M. McCracken[1,2] | **Kevin R. Ward**[1,2,3] | **Mohamad Hakam Tiba**[1,2]

[1]Department of Emergency Medicine, University of Michigan, Ann Arbor, Michigan, USA

[2]The Max Harry Weil Institute for Critical Care Research and Innovation, University of Michigan, Ann Arbor, Michigan, USA

[3]Department of Biomedical Engineering, University of Michigan, Ann Arbor, Michigan, USA

Correspondence
Mohamad Hakam Tiba, Department of Emergency Medicine, University of Michigan, 2800 N. Plymouth Road, North Campus Research Complex, Ann Arbor, MI 48109, USA.
Email: tibam@med.umich.edu

Funding information
U.S. Department of Defense, Grant/Award Number: W81XWH-18-1-0033; Max Harry Weil Institute for Critical Care Research and Innovation

KEYWORDS: abdominal organ injury, aorta, GROA, non-compressible hemorrhage, REBOA, resuscitation, shock, inflatable device

1 | INTRODUCTION

Management of both battlefield and civilian trauma victims suffering from non-compressible torso hemorrhage (NCTH) remains a significant challenge with exsanguination continuing to be the leading cause of mortality from potentially survivable injuries.[1–4] Death from hemorrhage may occur rapidly and often before arrival at a medical facility capable of providing definitive surgical hemostasis.[2,5] Such challenges present a critical need for new technologies in the realm of pre-hospital and even early in-hospital hemostasis. Whether in the austere (battlefield) or the civilian prehospital emergency medical services environment, the ability to treat NCTH is very limited.[6] Furthermore, logistical challenges such as transportation delays and mass casualty incidents highlight the need for providing temporary hemostasis before the arrival at a high-level care facility. In summary, most patients who succumb to NCTH do so in the pre-hospital or austere environment before surgical care because of limited resources. Even the ability to provide rapid temporary hemostasis in the emergency department or trauma center environment can present significant challenges.

Surgical management remains the pinnacle treatment for NCTH, however, for the reasons mentioned above, is not viable as an early intervention near the point of injury. Coupled with the lack of resources for early resuscitation, mechanical hemorrhage control continues to be of interest to employ following the determination of severe hemorrhage in a forward setting.[7] Current approved technologies for mechanical hemostasis include extremity and junctional tourniquets, pelvic binders, and endovascular balloon occlusion of the aorta. Additional investigational techniques such as abdominal insufflation and intra-abdominal foams are at various stages of development but are not currently cleared for clinical use.[8–10]

2 | AORTIC OCCLUSION

Occlusion of the descending aorta will certainly reduce or cease intraabdominal and pelvic hemorrhage. While

Brendan M. McCracken, Kevin R. Ward, and Mohamad Hakam Tiba are equal contributions to this article.

feasible in the trauma center and operating room, surgical occlusion via thoracotomy and aortic cross-clamping is not feasible in the field or routinely feasible in the non-trauma center emergency department setting. Recent efforts to save victims of severe NCTH have resulted in the resurrection of balloon occlusion of the aorta as a potential to extend the window of opportunity for definitive surgical care. The technique and technology currently termed Resuscitative Endovascular Balloon Occlusion of the Aorta (REBOA) has demonstrated promise in this regard.[11–14] The REBOA device can be placed allowing for aortic occlusion at various levels (Zones 1, 2, 3) depending on where the location of NCTH is suspected. REBOA has gained popularity[11–15] but is currently limited to trauma centers[16] and while it has been successfully implemented in trauma centers and limited combat applications,[17] has not yet been fully utilized in prehospital or austere environments for multiple logistic reasons. The largest barrier to implementation may be the time between injury and aortic occlusion, which is driven by the necessity for vascular access requiring highly skilled operators or imaging equipment, or failure to cannulate the femoral artery.[18–20]

The other approved mechanical method available for aortic occlusion is the Abdominal Aortic Junctional Tourniquet (AAJT). The AAJT has been demonstrated to be capable of occluding the infrarenal aorta and thus may be effective as an aortic zone 3 occlusion device for control of bleeding below that level such as pelvic hemorrhage.[9,21–24] It achieves this by the mechanical targeting of pressure directly downward towards the abdominal aorta. This is different from the previously used technologies called the military antishock trousers (MAST) or pneumatic antishock garments (PASG) which have been determined to be ineffective for treating abdominal or pelvic tamponade of severe arterial bleeding and are no longer recommended.[25] The abdominal/pelvic compartment of the MAST/PASG devices is pneumatically inflated and produces circumferential pressure around the lower torso. There is no discrete directed inward pressure provided to the abdominal or pelvic cavity such as that produced by the AAJT. As such, unless intra-abdominal pressure is increased above systolic arterial blood pressure, bleeding will continue and could potentially be worsened. Even with the AAJT, because of infrarenal occlusion (Zone 3), there is the potential of the AAJT to increase hemorrhage if bleeding is occurring from the liver or spleen (Zone 2) due to increased hydrostatic pressures that may be produced proximal to the site of occlusion.

To further address the unmet need for temporary prehospital stabilization of the victim of non-compressible abdominal hemorrhage, our team has developed two technologies known as Gastroesophageal Resuscitative Occlusion of the Aorta (GROA),[26,27] and the Intra-Peritoneal Hemostasis Device (IPHD).[28] The main motivation for the development of these technologies is to allow for the rapid treatment of NCTH in austere combat environments, civilian pre-hospital, and higher echelons of care including emergency department and trauma center settings when surgical expertise and/or resources may be delayed. In this narrative review, we aim to summarize the design and application features of these devices, as well as summarize previous pre-clinical testing related to the treatment of NCTH.

3 | DESCRIPTION OF GROA AND STUDIES

GROA is an investigational device and approach which utilizes aortic impingement via a gastroesophageal balloon that is orogastrically placed into the stomach. The device and approach leverage the anatomical relationship of the abdominal aorta, stomach, and thoracic vertebral bodies. The design and dimensions (described below) were based on morphomic analysis of human adult abdominal and chest CT scans (Figure 1) similar to that used to develop recent REBOA technology.[29] In two previous investigations, we have shown that when the device is inserted, an external pressure system is activated, and the balloon inflated, it can provide high zone-2 (celiac or supraceliac) aortic occlusion by compressing the aorta between the posterior wall of the stomach and the anterior thoracic vertebrae. The main components of the system include a gastroesophageal tube with an ellipsoid-shaped balloon, an air pump/pressure gauge assembly, and an adjustable external compression system (Figure 2). Unlike the Sengstaken-Blakemore tube, the GROA gastric balloon is larger and has less complaint in order to produce aortic occlusion over an area where the aortic is expected to lie in relationship with the thoracic vertebra. The gastroesophageal tube includes lumens for suction and evacuation of gastric contents, an air vent to avoid vacuum/pneumatic tension in the stomach, and balloon inflation and deflation. A 14F gastric tube is placed through a central lumen in the GROA device and used to guide the balloon by the orogastric route into the stomach. The air pump/pressure gauge assembly allows for controlled balloon inflation/deflation and visual feedback on the pressure of the balloon. The external compression system consists of a back plate and an abdominal plate. When activated, this system prevents lateral and anterior deflection of the balloon, keeping the balloon over the aorta. The balloon inflates to an ellipsoid shape that provides the structure necessary to occlude

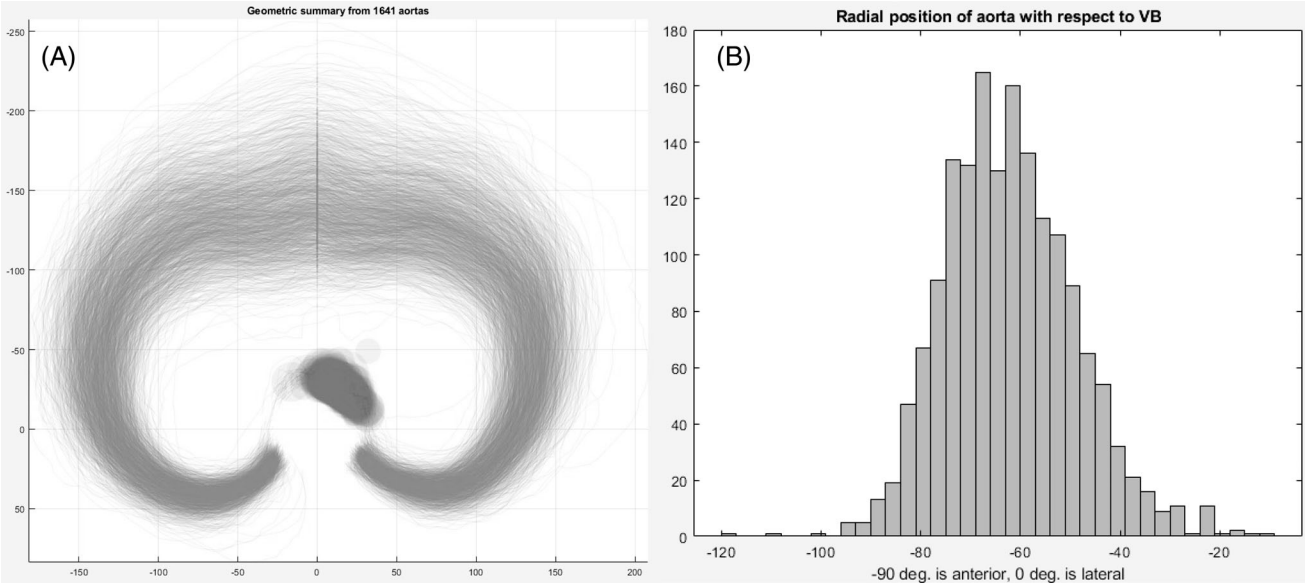

FIGURE 1 Left panel (A); Morphomic analysis of the aorta position in relation to the inferior aspect of the vertebral body of T10 in 1641 war fighter-aged subjects. The center of the vertebral body in the axial plane is used as the origin. Right panel (B); frequency of the radial position of the aorta with respect to the vertebral body in the same population

the aorta when an external pressure system is applied to the epigastric area.

Our initial GROA study aimed at evaluating the feasibility of achieving aortic occlusion and exploring the physiological tolerance to the device compared to REBOA (ER-REBOA, PRYTIME Medical, Boerne, TX) over application times ranging from 30 to 90 min in a swine model of controlled hemorrhagic shock and resuscitation.[26] In this study, aortic occlusion was achieved in every GROA application and 15 out of 16 animals treated with GROA survived the duration of the device application period. Only two animals in the 90-min occlusion group (2 out of 6) were able to be resuscitated to survive after the device was removed suggesting that 90 min of aortic occlusion, while possible, is not well tolerated in this model.

Survival rates for animals treated with REBOA using this model were also very similar to GROA across all groups. In the 30 and 60-min application groups for both GROA and REBOA, 9 out of 10 animals survived the post-resuscitation period. No animals receiving the 90-min REBOA intervention survived the post-resuscitation period which further suggests that the poor outcome was related to the aortic occlusion itself and not specific to the device used for occlusion. Overall, this study concluded that up to 60 min of aortic occlusion with GROA was both tolerated and feasible, and while the GROA device could create and maintain occlusion and survival for 90-min, resuscitation following aortic occlusion for this time was not well tolerated.

In the above study, we attached an ultrasonic flow probe to the hepatic artery. During activation of the GROA device, loss of hepatic artery blood flow was noted during aortic occlusion (Figure 2, bottom panel). This indicates that GROA was effective in creating a high zone 2 aortic occlusion at or superior to the hepatic artery, and the survival rate and overall tolerance to the GROA device appears very similar to the already well characterized and FDA-cleared REBOA device.

In a follow-up study, GROA's ability to stanch NCTH was evaluated using a highly lethal grade V liver laceration model comparing GROA to REBOA and controls.[27] Occlusion time in this study was limited to 60-min based on the previous tolerance testing.[26] The model was rapidly lethal for the control group resulting in a median survival time of only 10.5 min from the onset of the injury. This study reaffirmed the ability to successfully apply GROA and achieve aortic occlusion in all animals. In overall survival, GROA was successful at prolonging survival compared to controls, with no difference in survival noted between the GROA and REBOA devices. The survival benefit observed in this study strongly suggested that the lethal hemorrhage was quickly stopped by GROA and resulted in rapid improvement of mean arterial pressure (MAP) and mixed venous oxygen saturation (SvO_2). Further evidence of hemorrhage control was observed as the physiologic benefits of aortic occlusion of GROA were maintained without significant deterioration for the duration of the intervention period. Inflammatory markers (cytokines IL-6 and IL-8) were elevated in both

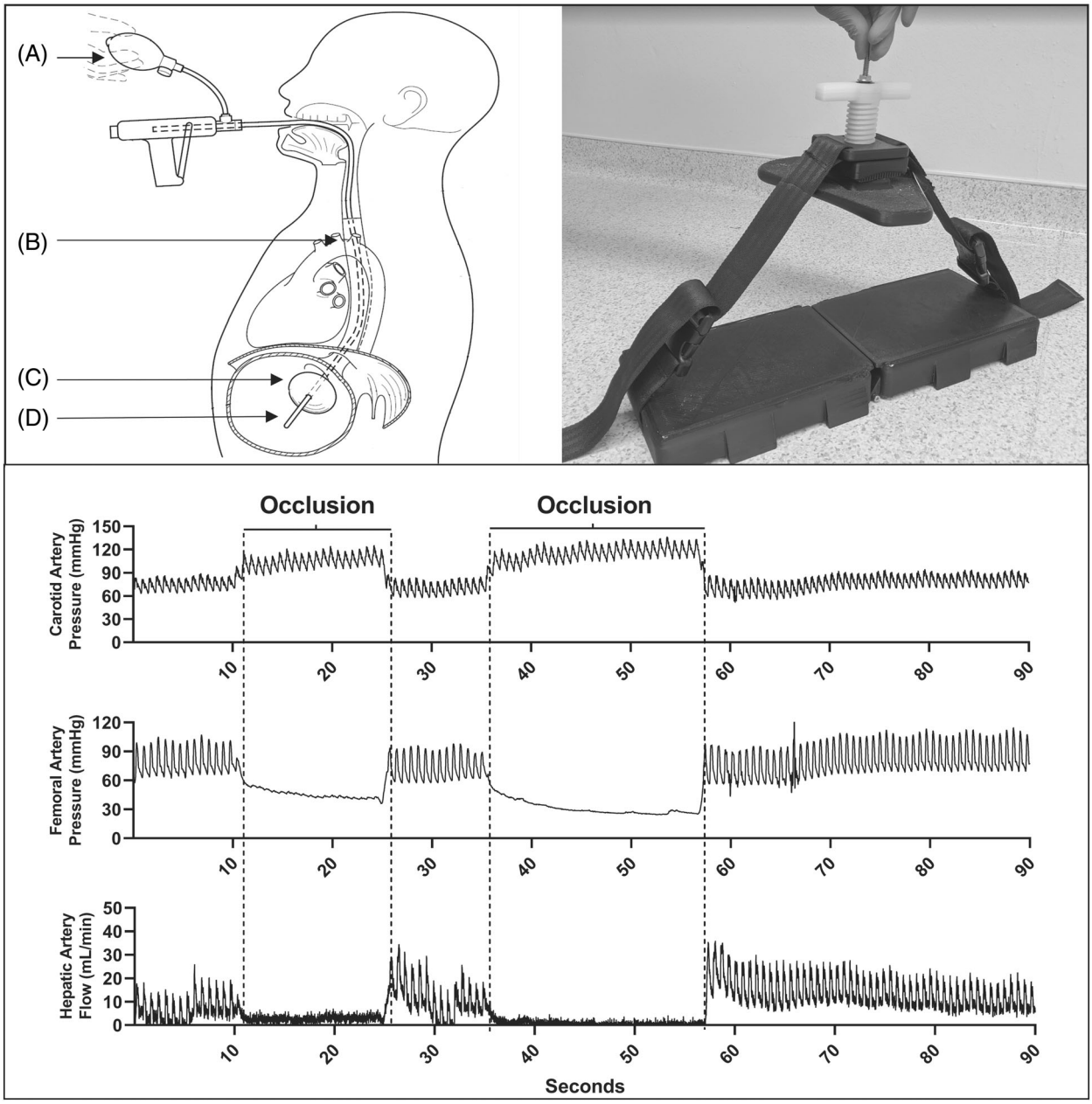

FIGURE 2 Top left panel; an illustrated version of the GROA device applied to a human; (A) air pump/pressure gauge assembly, (B) gastroesophageal tube (C) ellipsoid shaped gastric balloon, (D) retractable 14F tip. Top right panel; adjustable external compression system. Bottom panel; arterial pressure from the carotid and femoral arteries, and hepatic artery flow during GROA occlusion

GROA and REBOA aortic occlusion groups and therefore were attributed to aortic occlusion, rather than the occlusion device itself. While there was no significant difference in survival between the REBOA and GROA groups, both GROA and REBOA were pre-placed prior to the injury. A description of all models reviewed, including survival data, is presented in Table 1.

In our experience (data not published), we are routinely able to place the GROA balloon catheter with the accompanying abdominal plate and activate the device to achieve aortic occlusion in under 120 s. Had the GROA and REBOA devices been actively placed after the start of hemorrhage, a difference in survival favoring GROA would have likely been detected. The time to application of REBOA (from injury onset) remains the largest limitation to its use as an effective pre-hospital intervention. With an application time ranging from 34 to 57 min reported in a clinical feasibility study for the treatment of cardiac arrest,[18] the time to REBOA application exceeds time periods in which as many as 45% of deaths due to severe hemorrhage in the field occur. This application time is likely largely due to difficulties in cannulating the

TABLE 1 Description of models used to evaluate GROA and IPHD

Study	Controlled hemorrhage (%), (min)	Source of uncontrolled hemorrhage	Uncontrolled hemorrhage time (min)	Shock classification	MAP at start of intervention (mmHg)	Lactate at start of intervention (mEq/L)	Duration of intervention (min)	Survival: intervention (%)	Survival: monitoring (%)
GROA - Tolerance	35, 30	N/A	N/A	Class III-IV	33.5 (5.10)	4.03 (1.75)	30, 60, 90	100, 100, 83	80, 100, 33
GROA - Survival	30, 20	Liver Laceration	2	Class IV	27.1 (5.65)	2.64 (0.95)	60	100	37.5
IPHD	30, 20	Liver, Spleen, Kidney	2	Class IV	24.3 (3.73)	2.34 (0.29)	60	100	0

Note: Data are presented as mean (standard deviation) or a percentage.

femoral artery.[27] While we envision military medics and civilian first responders being able to effectively apply the GROA device, future feasibility studies will need to be performed.

Unlike REBOA, in a real-time clinical use scenario, the GROA device will require deflation during surgery limiting its use during surgery and ongoing hemorrhage. However, we have recently completed a study using the same model of lethal liver hemorrhage to demonstrate the feasibility of transitioning GROA to REBOA without any change in survival. This provides a value proposition for both prehospital and emergency department/trauma center use where GROA could be placed and activated allowing time for near-term placement of REBOA for transport, surgery, or other hemostatic strategies such as interventional radiology.

In the combination of studies, the hemodynamic response created by GROA is similar to REBOA. Immediate improvement in MAP was observed in response to GROA and REBOA and there were no differences between the aortic occlusion methods in MAP, central venous pressure, pulmonary artery pressure, and lactate burden. Further, there were no differences in resuscitation requirements or organ function measured by serum chemistry, thromboelastography, or inflammatory cytokines (IL-6 and IL-8). Only minor differences in SvO_2, and end-tidal CO_2 during GROA occlusion were noted. An elevation of airway pressure was observed and associated with the GROA intervention in all animals. The increase in airway pressure was, however, mild and transient averaging 31 cm H_2O (ranging from 25 to 39 cm H_2O) and did not affect ventilation or oxygenation parameters. While intrabdominal pressure is expected to increase, it was not measured during GROA use. This important information should be collected in the future, especially during the reperfusion period to evaluate for evidence of the development of post-surgical abdominal compartment syndrome.

In both studies, histological analyses of stomach tissue for animals undergoing occlusion using GROA demonstrated changes consistent with mild ischemia likely produced by the pressure that the balloon creates when the abdominal plate is tightened. However, similar changes were noted in REBOA animals pointing towards general ischemia from the aortic occlusion as a potential contributor. The final extent of these changes cannot be known until longer survival studies are performed. No histologic changes were noted in the aorta in either occlusion method.

These studies demonstrated that GROA was consistently effective at creating aortic impingement and thus temporarily capable of stanching lethal hemorrhage and prolonging survival. Considering the survival benefit in

combination with a fast and easy application technique, GROA appears to be a promising technique to improve survival from non-compressible abdominal hemorrhage.

4 | DESCRIPTION OF IPHD AND STUDIES

The IPHD is another investigational device being explored for the treatment of NCTH. Its development and testing were inspired by the proposed mechanisms of action of ResQFoam (Arsenal Medical, Inc., Waltham, MA). Developed with over 30 million dollars in funding by the Department of Defense, it is a self-expanding polyurethane designed to be injected into the abdominal cavity to stanch hemorrhage by covering and compressing bleeding surfaces and has been shown to improve survival in a large animal lethal, closed-cavity, hepatoportal injury model[30,31] and is currently undergoing clinical trial. Such a strategy may have implementation advantages over REBOA, especially in the field setting. However, there may be potential drawbacks since the expansion of the material cannot be controlled or titrated after injection and has been associated with complications such as bowel injury and possibly abdominal compartment syndrome.[32] In addition, patients receiving this therapy will require surgery to remove the material even if techniques such as interventional radiology are successful in creating definitive hemostasis.

Since the major proposed mechanisms for the hemostasis produced by ResQFoam is the pressure produced by the expanding foam, we hypothesized that insertion of an inflatable balloon into the peritoneal cavity can create direct or indirect pressure on hemorrhaging sites to produce hemostasis but without some of the previously mentioned drawbacks of ResQFoam. The core component of the device is a square, pillow-shaped, and semi-compliant balloon intended for intra-peritoneal placement (Figure 3). Prior to use, the balloon is pre-loaded inside a trocar-tipped applicator. Intraperitoneal access is gained through a small abdominal incision. The introducer is placed through the incision and a plunger is used to deploy the balloon into the peritoneal space where it can then be inflated. The balloon is roughly 18 cm × 18 cm × 10 cm when inflated and attached to an externalized line which allows for inflation/deflation. While we are still exploring the optimal shape of the balloon, the square shape was chosen to maximize the balloon surface contact area with abdominal organs and the anterior abdominal wall (324 cm^2 as opposed to ~254 cm^2 for a round-shaped balloon). Similar to the GROA device, the inflation/deflation mechanism of the IPHD also utilizes an air pump and pressure gauge assembly.

In a pilot study, the IPHD was evaluated for its ability to temporarily control hemorrhage and subsequently improve survival in a model of rapidly lethal, multi-organ hemorrhage including a grade-V liver laceration (the same method as used in the aforementioned GROA study) combined with a severe spleen and kidney laceration.[27,28] The group of animals treated with IPHD was compared to controls (no IPHD) for survival, hemodynamics, and other metrics of shock. All control animals (3/3) died within 15–43 min from injury while all IPHD-treated animals (5/5) survived the duration of the 60-min intervention period. Animals treated with IPHD responded to the treatment with an overall improvement in MAP, shock index, SvO_2, and cardiac output during the intervention period; control animals steadily decreased in these parameters until death endpoints were met. To underscore the severity of the created injuries, all animals in the IPHD group died after deflation of the device due to reactivation of hemorrhage.

The study concluded that the IPHD intervention was effective at prolonging survival compared to controls, due to the slowing or stopping of hemorrhage from multiple organ sources supporting the concept that when the IPHD is activated within a closed space (peritoneum), the balloon likely causes direct tamponade when contacting bleeding surfaces and indirect tamponade by displacing nonbleeding tissues that then contact and apply pressure to the hemorrhaging surfaces resulting in hemostasis.

Of particular interest and a potential advantage over both GROA and REBOA is the fact that the IPHD produced hemostasis without the need to occlude the aorta despite the severity of injuries. With the application of additional pressure to the external abdomen, we were also able to easily occlude the aorta without occluding hepatic artery blood flow as measured by an ultrasonic flow probe (Figure 3, bottom). Similar to GROA, the IPHD would need to be deactivated and removed at the time of surgery. However, as pointed out earlier, the transition from the IPHD to REBOA should be feasible allowing for control of NCTH at the time of surgery.

The study is limited as a pilot study and underpowered to detect discrete hemodynamic effects, however, the preliminary results generated indicate the feasibility of the application, a survival benefit, and other favorable physiological effects. Based on these effects, additional research for such a device is warranted for NCTH.

5 | IPHD AND GROA SUMMARY EFFECT ON SURVIVAL VERSUS CONTROL

Since the models used for the pilot IPHD and GROA survival studies were nearly identical in their lethality, it is feasible to pool control data from both studies and

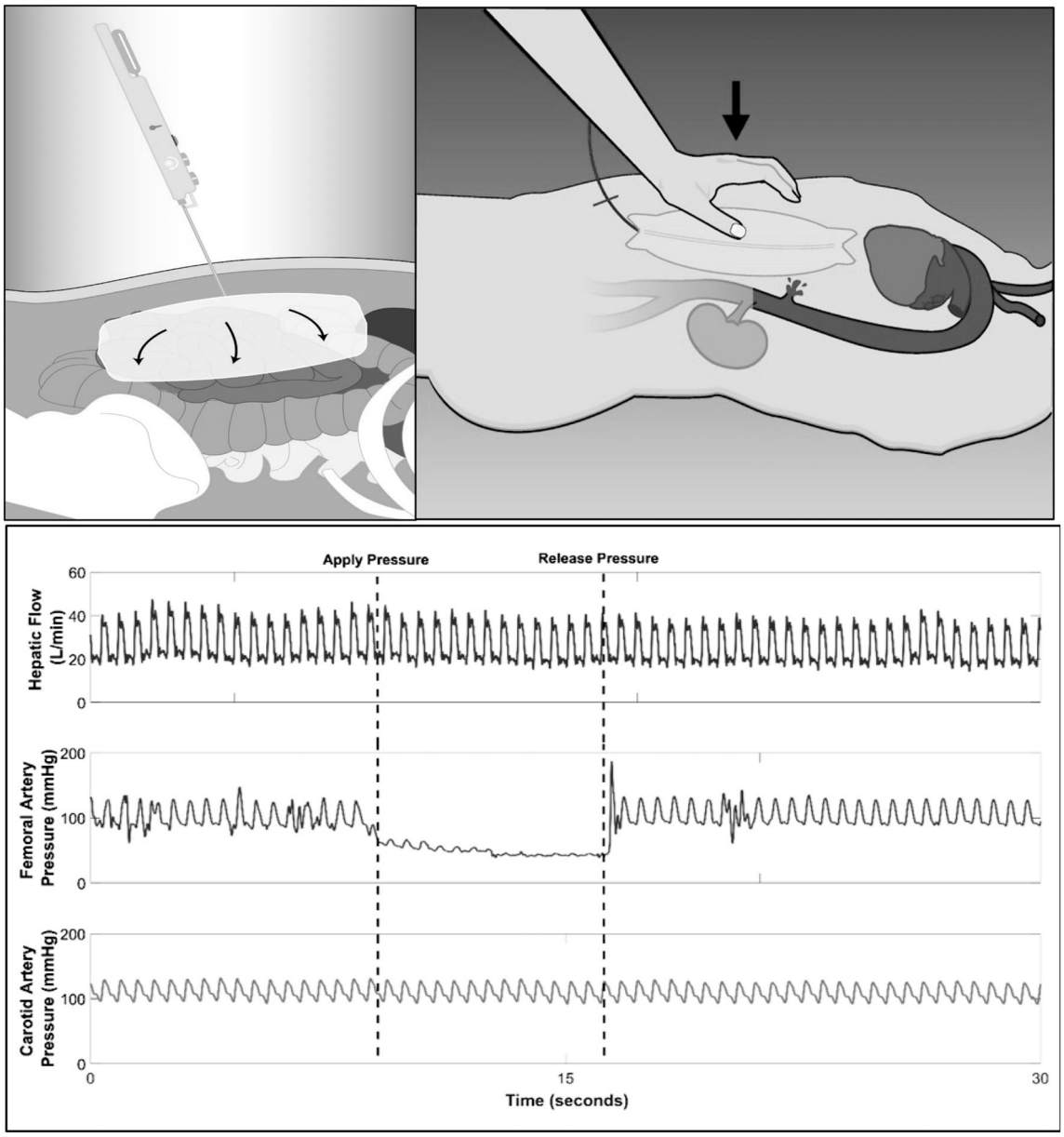

FIGURE 3 Top left panel; illustration of an automated applicator and intraperitoneal balloon deployment. Top right panel; illustration of the IPHD balloon inflated after intraperitoneal deployment and external pressure being applied for selective aortic occlusion. Bottom panel; arterial pressure from the carotid and femoral arteries, and hepatic artery flow during user-selected aortic occlusion

present the survival of GROA and IPHD against all controls. A Kaplan Meier curve showing survival from the onset of injury is presented in Figure 4. A log-rank test of the survival curves on the pooled data shows a similar and significant survival effect from both GROA and IPHD relative to controls. The GROA median survival was 146 min after injury and 90 min for the IPHD, while median survival across all controls was only 13 min $p = .0039$. Also of note is that all animals receiving either intervention survived the duration of the intervention period and expired during the resuscitation and post-resuscitation phases due to renewed massive hemorrhage following device removal, or from reperfusion injury. These data suggest there is a distinct survival benefit associated with each technology and intervention when compared to controls.

6 | ADVANTAGES OF GROA AND IPHD

With 45% of deaths from severe hemorrhage occurring in the field[33,34] new technologies to stop or slow hemorrhage in the pre-hospital or austere environment will be

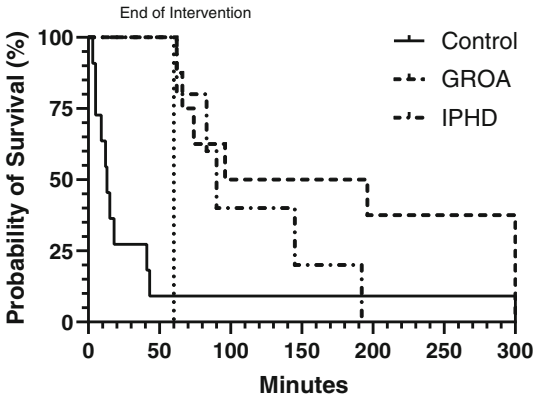

FIGURE 4 Kaplan Meier plot of survival proportions in a preclinical swine model of rapidly lethal abdominal hemorrhage; GROA ($n = 8$) and IPHD ($n = 5$) treated animals are represented as dashed and dotted dashed lines, respectively, and plotted against controls ($n = 11$) (solid line).

required if this statistic is to significantly improve. These pre-clinical studies for both GROA and IPHD suggest that either approach may be effective for mechanical stanching of high zone-2 torso hemorrhage and are potentially feasible for pre-hospital application. GROA and the IPHD both hold application advantages that could considerably reduce the time to mechanical hemorrhage control after injury.

The GROA device is less invasive than other techniques and does not require any surgical intervention or imaging to be placed. With a physiologic tolerance profile similar to REBOA, these characteristics may favor GROA as a first-line tool or initial approach for suspected cases of massive hemorrhage that would require aortic occlusion. GROA's use as an adjunct or bridge to REBOA or surgical intervention would seem to be feasible as indicated earlier. Therefore, it is envisioned that military medics, civilian first-responders (paramedics), and hospital trauma providers would also be able to effectively apply the GROA device.

The IPHD requires a slightly more invasive approach for application as it is deployed percutaneously within the abdomen. Despite this and given the emergence of other intraperitoneal resuscitation techniques such as ResQFoam, we envision the application of this technology to be feasible. Like GROA, the device was rapidly placed and removed without complication in the pilot study.

The IPHD may also offer a more titratable approach for managing hemorrhagic abdominal injuries. The ability to titrate pressure and easily remove the device through the application incision does not commit the patient to subsequent laparotomy if less invasive treatments such as interventional radiology may be sufficient for definitive hemostasis. An additional benefit of the IPHD also includes the potential for selective occlusion of the aorta. While the IPHD has demonstrated the capability of hemorrhage control from lethal hepatoportal injury without requiring occlusion of the aorta, for some injury patterns such as those to lower abdominal arteries (renal or iliac), selective occlusion of the aorta is possible if warranted.

Lastly, a considerable benefit common to both devices is the preservation of physiologic reserve. In all three preclinical studies, important hemodynamic parameters rapidly improved after the devices were activated. Reducing hemorrhage while maintaining perfusion to the heart and brain, or at minimum slowing hemodynamic deterioration with a mechanical device as early as possible, may ultimately limit the accumulation of lethal levels of oxygen debt. This effect may be paramount to optimizing resuscitation once more advanced care and definitive hemostasis are available.

A final consideration is that all three of the studies covered in this review are preliminary in nature and focused on the feasibility of the application, physiologic tolerance, and survival during the intervention, and over a short post-resuscitation monitoring period. Beyond that, all the studies remain underpowered to detect discrete differences in other outcomes, that is, hemodynamics between methods. This does not, at this time, allow for the assessment of superiority or non-inferiority relative to any other technologies used for non-compressible hemorrhage, approved or investigational. Despite this, we believe that all three studies have generated powerful preliminary data which gives a certain confidence to the feasibility of application and tolerance to the devices, a clear initial survival benefit from the devices' application, and evidence of improved hemodynamics. Regardless, as the technologies described here move forward, long-term pre-clinical studies and human application feasibility studies are needed, and eventually, clinical trials, where we may begin to, truly understand the extent of the physiologic effects, survival benefits, and adverse consequences of their application. The next phase of development and testing of these devices includes design refinement and testing in perfused cadaver models.

7 | OVERALL CONCLUSION

Two emerging technologies discussed in this review were designed with a common target objective: Early-phase transitory control of non-compressible abdominal hemorrhage which is capable of temporarily prolonging survival during transport or before advanced surgical or resuscitative care is available. Both technologies share the promise

of pre-hospital application, can be deployed quickly and consistently, and both have been shown to improve hemodynamics, reduce shock, preserve physiologic reserve, and ultimately prolong survival from otherwise rapidly lethal exsanguination.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support from Katelyn Murphy and the staff of the Max Harry Weil Institute for Critical Care Research and Innovation.

FUNDING INFORMATION

The GROA device studies and development were supported in full by a grant from the United States Department of Defense, contract number: W81XWH-18-1-0033. The IPHD device study and development were supported internally by the Max Harry Weil Institute for Critical Care Research and Innovation.

CONFLICT OF INTEREST

BMM, KRW, and MHT have intellectual property associated with the devices discussed in this review through the University of Michigan. These technologies have been licensed to Precision Trauma LLC. Kevin R. Ward has equity in the company.

ORCID

Mohamad Hakam Tiba https://orcid.org/0000-0002-6789-7532

REFERENCES

1. Eastridge BJ, Hardin M, Cantrell J, Oetjen-Gerdes L, Zubko T, Mallak C, et al. Died of wounds on the battlefield: causation and implications for improving combat casualty care. J Trauma. 2011;71:S4–8.
2. Eastridge BJ, Mabry RL, Seguin P, Cantrell J, Tops T, Uribe P, et al. Death on the battlefield (2001-2011): implications for the future of combat casualty care. J Trauma Acute Care Surg. 2012;73:S431–7.
3. Kisat M, Morrison JJ, Hashmi ZG, Efron DT, Rasmussen TE, Haider AH. Epidemiology and outcomes of non-compressible torso hemorrhage. J Surg Res. 2013;184:414–21.
4. Spinella PC. Zero preventable deaths after traumatic injury: an achievable goal. J Trauma Acute Care Surg. 2017;82:S2–8.
5. Eastridge BJ, Holcomb JB, Shackelford S. Outcomes of traumatic hemorrhagic shock and the epidemiology of preventable death from injury. Transfusion. 2019;59:1423–8.
6. Jenkins DH, Rappold JF, Badloe JF, Berséus O, Blackbourne COLL, Brohi KH, et al. Trauma hemostasis and oxygenation research position paper on remote damage control resuscitation: definitions, current practice, and knowledge gaps. Shock. 2014;41(Suppl 1):3–12.
7. Chang R, Eastridge BJ, Holcomb JB. Remote damage control resuscitation in austere environments. Wilderness Environ Med. 2017;28:S124–S34.
8. Gruionu G, Gruionu LG, Duggan M, Surlin V, Patrascu S, Velmahos G. Feasibility of a portable abdominal insufflation device for controlling intraperitoneal bleeding after abdominal blunt trauma. Surg Innov. 2019;26:662–7.
9. Klein MK, Tsihlis ND, Pritts TA, Kibbe MR. Emerging therapies for prehospital control of hemorrhage. J Surg Res. 2019;248:182–90.
10. Velmahos GC, Spaniolas K, Tabbara M, Duggan M, Li Y, de Moya M, et al. Abdominal insufflation decreases blood loss without worsening the inflammatory response: implications for prehospital control of internal bleeding. Am Surg. 2008;74:297–301.
11. Linnebur M, Inaba K, Haltmeier T, Rasmussen TE, Smith J, Mendelsberg R, et al. Emergent non-image-guided resuscitative endovascular balloon occlusion of the aorta (REBOA) catheter placement: a cadaver-based study. J Trauma Acute Care Surg. 2016;81:453–7.
12. Moore LJ, Brenner M, Kozar RA, Pasley J, Wade CE, Baraniuk MS, et al. Implementation of resuscitative endovascular balloon occlusion of the aorta as an alternative to resuscitative thoracotomy for noncompressible truncal hemorrhage. J Trauma Acute Care Surg. 2015;79:523–30; discussion 30–2.
13. Morrison JJ, Galgon RE, Jansen JO, Cannon JW, Rasmussen TE, Eliason JL. A systematic review of the use of resuscitative endovascular balloon occlusion of the aorta in the management of hemorrhagic shock. J Trauma Acute Care Surg. 2016;80:324–34.
14. Sadek S, Lockey DJ, Lendrum RA, Perkins Z, Price J, Davies GE. Resuscitative endovascular balloon occlusion of the aorta (REBOA) in the pre-hospital setting: an additional resuscitation option for uncontrolled catastrophic haemorrhage. Resuscitation. 2016;107:135–8.
15. Reva VA, Horer TM, Makhnovskiy AI, Sokhranov MV, Samokhvalov IM, DuBose JJ. Field and en route resuscitative endovascular occlusion of the aorta: a feasible military reality? J Trauma Acute Care Surg. 2017;83:S170–S6.
16. Brenner M, Bulger EM, Perina DG, Henry S, Kang CS, Rotondo MF, et al. Joint statement from the American College of Surgeons Committee on Trauma (ACS COT) and the American College of Emergency Physicians (ACEP) regarding the clinical use of resuscitative endovascular balloon occlusion of the aorta (REBOA). Trauma Surg Acute Care Open. 2018;3:e000154.
17. Northern DM, Manley JD, Lyon R, Farber D, Mitchell BJ, Filak KJ, et al. Recent advances in austere combat surgery: use of aortic balloon occlusion as well as blood challenges by special operations medical forces in recent combat operations. J Trauma Acute Care Surg. 2018;85:S98–S103.
18. Brede JR, Lafrenz T, Kruger AJ, Søvik E, Steffensen T, Kriesi C, et al. Resuscitative endovascular balloon occlusion of the aorta (REBOA) in non-traumatic out-of-hospital cardiac arrest: evaluation of an educational programme. BMJ Open. 2019;9:e027980.
19. Davidson AJ, Russo RM, Reva VA, Brenner ML, Moore LJ, Ball C, et al. The pitfalls of REBOA: risk factors and mitigation strategies. J Trauma Acute Care Surg. 2017;84:192–202.
20. Lendrum R, Perkins Z, Chana M, Marsden M, Davenport R, Grier G, et al. Pre-hospital resuscitative endovascular balloon

occlusion of the aorta (REBOA) for exsanguinating pelvic haemorrhage. Resuscitation. 2019;135:6–13.
21. Croushorn J. Abdominal aortic and junctional tourniquet controls hemorrhage from a gunshot wound of the left groin. J Spec Oper Med. 2014;14:6–8.
22. Klotz JK, Leo M, Anderson BL, Nkodo AA, Garcia G, Wichern AM, et al. First case report of SAM? Junctional tourniquet use in Afghanistan to control inguinal hemorrhage on the battlefield. J Spec Oper Med. 2014;14:1–5.
23. Kragh JF, Kotwal RS, Cap AP, Aden JK, Walters TJ, Kheirabadi BS, et al. Performance of junctional tourniquets in normal human volunteers. Prehosp Emerg Care. 2015;19:391–8.
24. Kheirabadi BS, Terrazas IB, Miranda N, Voelker AN, Klemcke HG, Brown AW, et al. Long-term consequences of abdominal aortic and junctional tourniquet for hemorrhage control. J Surg Res. 2018;231:99–108.
25. Lyng J, Adelgais K, Alter R, Beal J, Chung B, Gross T, et al. Recommended essential equipment for basic life support and advanced life support ground ambulances 2020: a joint position statement. Prehosp Emerg Care. 2021;25:451–9.
26. Tiba MH, McCracken BM, Colmenero CI, Plott JS, Leander DC, Greer NL, et al. Gastroesophageal resuscitative occlusion of the aorta: physiologic tolerance in a swine model of hemorrhagic shock. J Trauma Acute Care Surg. 2020;89:1114–23.
27. McCracken BM, Tiba MH, Colmenero CI, Leander DC, Greer NL, Plott JS, et al. Gastroesophageal resuscitative occlusion of the aorta prolongs survival in a lethal liver laceration model. J Trauma Acute Care Surg. 2021;92:880–9.
28. McCracken BM, Tiba MH, Colmenero CI, Leander DC, Greer NL, Plott JS, et al. Novel intraperitoneal hemostasis device prolongs survival in a swine model of noncompressible abdominal hemorrhage. J Trauma Acute Care Surg. 2021;90:838–44.
29. Eliason JL, Derstine BA, Horbal SR, Wang NC, Holcombe SA, Chiu CH, et al. Computed tomography correlation of skeletal landmarks and vascular anatomy in civilian adult trauma patients: implications for resuscitative endovascular balloon occlusion of the aorta. J Trauma Acute Care Surg. 2019;87:S138–S45.
30. Duggan M, Rago A, Sharma U, Zugates G, Freyman T, Busold R, et al. Self-expanding polyurethane polymer improves survival in a model of noncompressible massive abdominal hemorrhage. J Trauma Acute Care Surg. 2013;74:1462–7.
31. Peev MP, Rago A, Hwabejire JO, Duggan MJ, Beagle J, Marini J, et al. Self-expanding foam for prehospital treatment of severe intra-abdominal hemorrhage: dose finding study. J Trauma Acute Care Surg. 2014;76:619–23. discussion 23-4.
32. Rago AP, Duggan MJ, Beagle J, Peev MP, Marini J, Hwabejire JO, et al. Self-expanding foam for prehospital treatment of intra-abdominal hemorrhage: 28-day survival and safety. J Trauma Acute Care Surg. 2014;77:S127–33.
33. Alarhayem A, Eastridge BJ. Junctional hemorrhage and prehospital time after injury: highlighting the need for novel strategies to control complex sources of hemorrhage and temporize survival to definitive care. Military Health System Research Symposium. Washington, DC: UT Health San Antonio, 2016.
34. Alarhayem AQ, Myers JG, Dent D, Liao L, Muir M, Mueller D, et al. Time is the enemy: mortality in trauma patients with hemorrhage from torso injury occurs long before the "golden hour". Am J Surg. 2016;212:1101–5.

How to cite this article: McCracken BM, Ward KR, Tiba MH. A review of two emerging technologies for pre-hospital treatment of non-compressible abdominal hemorrhage. Transfusion. 2022;62(S1):S313–S322. https://doi.org/10.1111/trf.16961