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Commentary on gaps in prehospital trauma care: education and bioengineering innovations to improve outcomes in hemorrhage and traumatic brain injury

Joshua B Brown ,[1] Martin Schreiber ,[2] Ernest E Moore,[3] Donald H Jenkins,[4] Eric A Bank,[5] Jennifer M Gurney[6,7]

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[1]Surgery, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
[2]Surgery, Oregon Health and Science University, Portland, Oregon, USA
[3]Surgery, Ernest E Moore Shock Trauma Center at Denver Health, University of Colorado Denver, Denver, Colorado, USA
[4]Surgery, University of Texas Health Science Center at San Antonio, San Antonio, Texas, USA
[5]Harris County Emergency Services District No 48, Katy, Texas, USA
[6]Defense Committees on Trauma, Joint Trauma System, JBSA Fort Sam Houston, San Antonio, Texas, USA
[7]Department of Surgery, San Antonio Military Health System, San Antonio, Texas, USA

Correspondence to
Dr Joshua B Brown; brownjb@upmc.edu

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SUMMARY
Hemorrhage remains the leading cause of preventable death on the battlefield and the civilian arena. Many of these deaths occur in the prehospital setting. Traumatic brain injury also represents a major source of early mortality and morbidity in military and civilian settings. The inaugural HERETIC (HEmostatic REsuscitation and Trauma Induced Coagulopathy) Symposium convened a multidisciplinary panel of experts in prehospital trauma care to discuss what education and bioengineering advancements in the prehospital space are necessary to improve outcomes in hemorrhagic shock and traumatic brain injury. The panel identified several promising technological breakthroughs, including field point-of-care diagnostics for hemorrhage and brain injury and unique hemorrhage control options for non-compressible torso hemorrhage. Many of these technologies exist but require further advancement to be feasibly and reliably deployed in a prehospital or combat environment. The panel discussed shifting educational and training paradigms to clinical immersion experiences, particularly for prehospital clinicians. The panel discussed an important balance between pushing traditionally hospital-based interventions into the field and developing novel intervention options specifically for the prehospital environment. Advancing prehospital diagnostics may be important not only to allow more targeted applications of therapeutic options, but also to identify patients with less urgent injuries that may not need more advanced diagnostics, interventions, or transfer to a higher level of care in resource-constrained environments. Academia and industry should partner and prioritize some of the promising advances identified with a goal to prepare them for clinical field deployment to optimize the care of patients near the point of injury.

INTRODUCTION
Exsanguination remains the leading cause of preventable death in both civilian and military trauma.[1,2] This occurs early, with a third of these deaths in the prehospital setting.[3] Tremendous progress in resuscitation science has been made with the development of damage control resuscitation focused on minimizing crystalloid and balanced blood product transfusion, and more recently whole blood resuscitation with early hemorrhage control.[4–7]

Strides have also been made in understanding the underlying mechanisms and phenotypes of hemorrhagic shock, as well as the physiological and immunological derangements that occur within minutes of injury.[8–11] Increasingly, these principles have been implemented closer to the point of injury, with prehospital blood, plasma, and tranexamic acid improving outcomes.[5,12,13] Traumatic brain injury (TBI) also represents a major source of mortality and morbidity.[14] Similarly, aggressive prehospital care to avoid hypotension, hypoxia, and hyperventilation has been shown to reduce mortality in severe TBI.[15]

During the inaugural HERETIC (HEmostatic REsuscitation and Trauma Induced Coagulopathy) Symposium in October 2022, a multidisciplinary panel of experts in prehospital trauma care was convened to discuss how the outcomes of patients with hemorrhagic shock could be improved. The panel focused on what educational and bioengineering breakthroughs are critical to advancing prehospital trauma care in both civilian and military settings, with a focus on the future.

CASE VIGNETTES
Two illustrative fictional case vignettes were created and presented to the panel to stimulate discussion followed by directed open-ended questions (table 1, table 2). The cases highlighted ongoing challenges in prehospital and early trauma care, drawing on experience from recent conflicts given the invited panel and moderators' experience to frame the cases and discuss care from the point of injury through role 2 early presentation. Given the interest in civilian applications as well, the panelists were asked to consider solutions for the rural or austere civilian environment that could make an impact in prehospital and early non-trauma center care despite the military focus of the vignettes.

Case 1 and discussion
A 26-year-old man involved in a mounted vehicle improvised explosive device (IED) blast sustained obvious injuries to the face, head, right lower extremity, and abdomen. Initial vital signs included a systolic blood pressure of 92 mm Hg, respiratory rate of 26 breaths per minute, and Glasgow Coma Scale score of 3, with 4 mm and sluggishly reactive pupils bilaterally. No significant external source of bleeding was identified. A nasopharyngeal airway was placed and the patient received 1 g of tranexamic acid and 2 units of cold-stored whole blood. During medevac, the patient received 2 units of fresh whole blood through a sternal intraosseous catheter and assisted ventilations with a bag

Table 1 Directed questions to panelists based on case one vignette

Case 1 TBI+mild shock	1. What biomedical technology do you think we need the most to improve diagnosis and triage in the field?
	2. What role for TBI biomarkers is there to help with triage and decrease patient transfers to get a CT scan?
	3. If we were going to revamp medic education, should we focus more on skills and procedures while relying on automated clinical decision support, or developing clinical judgement/decision making?
	4. What role do you see for simulation, virtual reality, and how far can that take us in training medics?

valve mask. At the role 2 facility, the patient underwent rapid-sequence intubation. The initial blood pressure was 98/24 mm Hg and he was noted to have a positive focused assessment with sonography for trauma examination.

In response to question 1 (table 1) posed after the point of injury in the case, the panelists identified two potential breakthrough bioengineering solutions that with advancement in technology level would significantly impact field care. The first is near-infrared spectroscopy (NIRS) for diagnosis of TBI. This technology uses the reflection of light in the 600 to 1000 nm range to detect fluid/hemoglobin at the interface with the brain. Asymmetrical absorption of the light on either side of the skull can indicate subdural, epidural, or extracranial hematoma. A handheld device (Infrascanner Model 2500; InfraScan, Philadelphia, PA) is available (figure 1). An initial pilot testing in a civilian air medical transport service suggested a sensitivity of 93% compared with head CT for identifying cranial hematomas.[16]

The other technology identified was ultrasound and three-dimensional ultrasound use in the prehospital or field setting. Several portable point-of-care ultrasound systems are available for prehospital use with reports of good accuracy; however, widespread adoption is lacking. One systematic review noted a change in management as a result of ultrasound findings in between 9% and 49% of trauma patients, with the greatest accuracy for pneumothorax and hemoperitoneum in the prehospital setting.[17] Evaluation of ultrasound in a combat setting found it changed therapy in 4% and altered the surgical priority in 43%, allowing a delay of surgery in 30% of wounded warfighters, improving overall triage accuracy.[18] Three-dimensional ultrasound employs volumetric imaging techniques to display a three-dimensional representation of internal structures, whereas four-dimensional or real-time three-dimensional ultrasound can show motion of the three-dimensional structures.[19] Commonly used in obstetrics and cardiovascular medicine, the panelists discussed how this technology provides better image quality, automated or computer-assisted image capture, processing, and identification of abnormal findings, advancing the field forward.

After posing question 2 (table 1) to the panel, glial fibrillar acidic protein (GFAP) was discussed as one of the most promising TBI biomarkers. Early work has shown its ability to discriminate between patients with and without traumatic intracranial lesions on head CT, with an area under the receiver operating characteristic curve of 0.88.[20] A proof-of-concept study in patients with stroke employed GFAP in the prehospital setting. However, this was deployed as part of a specialized mobile intensive care ambulance that was equipped with a full gas laboratory and required centrifugation and cold storage of plasma.[21] Indeed, the panel discussion revolved around the need for a whole blood sample for GFAP, and the breakthrough needed is technology to move this to a realistic point-of-care platform to be used in rapid triage and prehospital therapeutic decision making.

A potential benefit of better point-of-injury diagnosis of TBI using biomarkers or NIRS technology is allowing administration of therapies more selectively to patients with known TBI earlier. Therapies such as prehospital tranexamic acid and plasma have been beneficial in patients with confirmed intracranial hemorrhage from TBI which could be facilitated using these technologies.[22 23]

In response to questions 3 and 4 (Table 1), the panel thought that, although skills are important, it is critical to focus on developing judgment and critical thinking for decision making. In austere and combat situations with rapidly changing circumstances, this is especially vital. The panel thought that clinical decision support is important to reduce cognitive load for protocols and rote knowledge tasks to allow for better judgment and decision making from a 'big picture' perspective. They thought that immersion in a variety of clinical settings and roles was essential for prehospital clinicians, as well as the key role of timely and relevant feedback, which prior work has supported.[24 25] The panel also thought simulation has an important role in prehospital clinician training, especially for procedural skills. They thought that simulation was also valuable for teamwork and team dynamics training. In the discussion of simulation fidelity, many had examples of 'home grown' solutions and thought a low to medium quality in realism and materials was sufficient to be beneficial without the need to purchase the 'top of the line' simulation technology in most cases.

An important point brought up in this discussion was the key differences between military prehospital care and rural civilian prehospital care. Whereas the clinical challenges of limited field resources and access to definitive care may be analogous, the staffing, funding, and standardization are quite different. This makes deploying promising solutions more difficult to achieve in civilian prehospital systems, as there is much more variation in training and standards of care, as well as more funding and staffing challenges among rural emergency medical services in the USA. Dissemination and implementation would be particularly important in the civilian setting to understand how to adapt and promote effective adoption of prehospital innovations among different systems.

Table 2 Directed questions to panelists based on case two vignette

Case 2 Junctional hemorrhage with profound shock	1. In the prehospital environment how can we tell where they are bleeding from and what can we do about it? What is your science fiction wish list for dealing with exsanguinating hemorrhage in the prehospital setting?
	2. How do you think we can maintain educational requirements and skills for medics especially across a spectrum of experience and resources?
	3. Should we focus on moving existing therapeutics from the hospital to the field or developing novel therapies? Do we take the people, or technology, or existing capabilities to the field?
	4. To bring new or existing capabilities to a prehospital environment, how do we overcome the logistical hurdles to make diagnostics or therapeutics easier to execute and/or carry on to the battlefield?

Case 2 and discussion

A 33-year-old man involved in a dismounted IED blast sustained obvious injuries to the right upper extremity, right lower

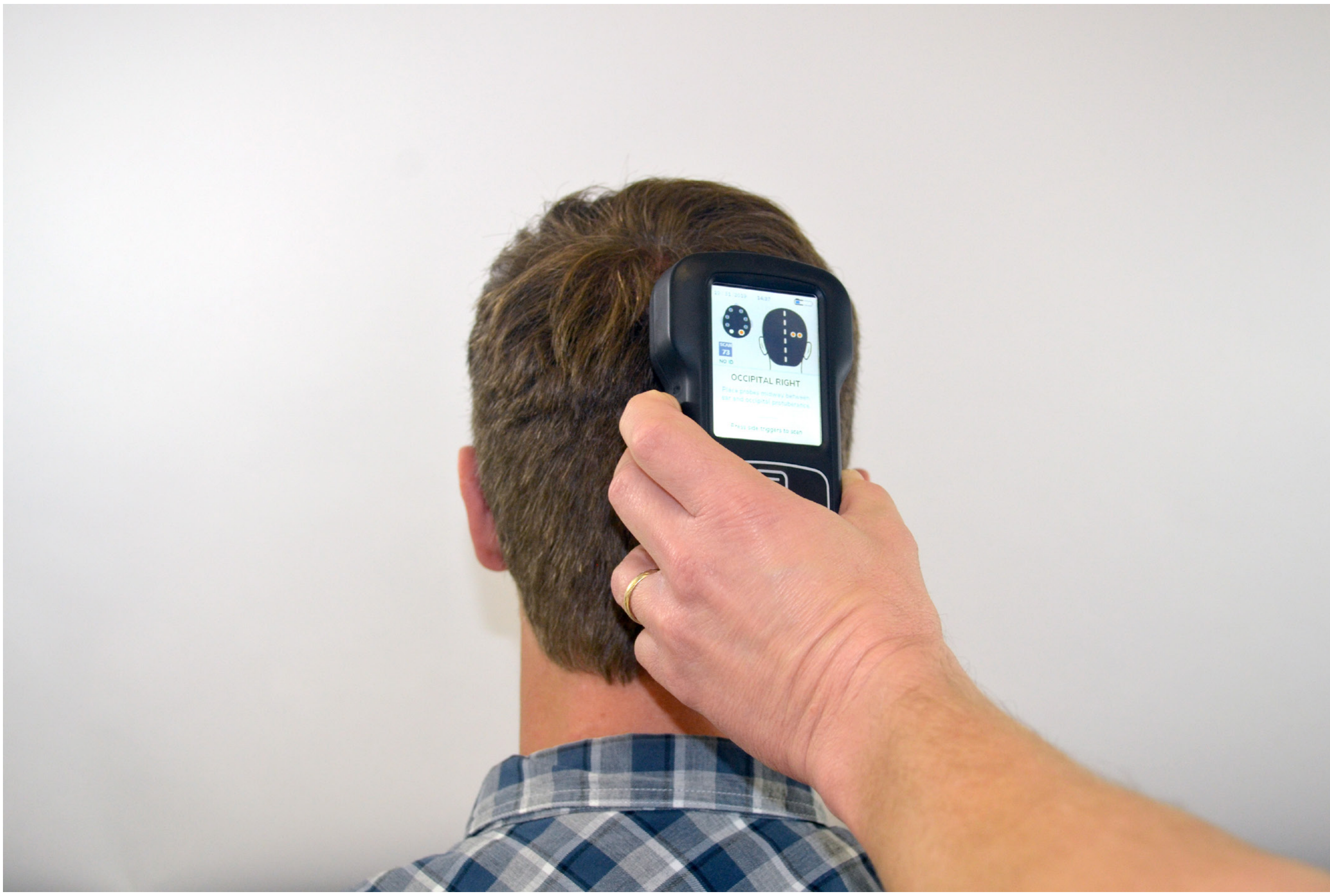

Figure 1 Infrascanner Model 2500 during scanning of the right occiput. Reproduced with permission from and provided courtesy of InfraScan (Philadelphia, PA).

Table 3 Top conceptual targets for improving prehospital and early trauma care.

1.	Improving prehospital identification/diagnosis of traumatic brain injury
2.	Improving prehospital identification/diagnosis of intra-cavitary hemorrhage
3.	Adapting existing promising technologies to make them simpler to deploy/use, portable, and facilitate widespread adoption in the prehospital setting
4.	Novel technology that is safe and minimally invasive to address non-compressible torso hemorrhage
5.	Educational innovation to focus on critical thinking and clinical immersion experience

extremity, and pelvis. He had an initial blood pressure of 60 mm Hg palpated. Combat application tourniquets were applied to the right arm and right leg, and a junctional tourniquet was placed in the right inguinal region, along with hemostatic dressings. Manual pressure was applied to the abdomen and the patient received 1 g of tranexamic acid, 1 g of calcium, 4 units of cold-stored whole blood, and 3 units of fresh whole blood. During medevac, the patient received 3 additional units of whole blood and an additional gram of tranexamic acid. On arrival at the role 2 facility, his blood pressure was 64/47, with a heart rate of 144 beats per minute and oxygen saturation of 67%.

In discussion of hemorrhage control approaches after posing question 1 (table 2), several options were forwarded. Resuscitative endovascular balloon occlusion of the aorta (REBOA) was discussed as an option that needs technical advances to be practical. Improvements in training and deployment to make it feasible across a wide variety of operational and rural civilian environments are necessary. Prehospital REBOA has been deployed and a case series from the London helicopter emergency medical services group demonstrated technical success, although a high rate of vascular complications (77%) occurred even in a physician-staffed helicopter service.[26]

Another option discussed was self-expanding injectable foam for non-compressible abdominal hemorrhage. This technology holds promise,[27] but is still in investigational stages for human trials.[28] Additional breakthroughs would need to be aimed at reducing the invasiveness of peritoneal cavity access to administer the foam and operationalizing it for field deployment.[29] This solution was of particular interest in the military setting as, depending on its ultimate performance, it may be a way to delay the immediacy of surgical capability needs in prolonged casualty care scenarios. Another interesting option discussed was prehospital cell-saver technology. Developing a portable or compact unit for far-forward deployment or at rural hospitals could mitigate limitations in blood supplies in these phases of care. A group has developed a proof-of-concept prototype portable device for austere or military environments, but further testing is required in a clinical setting.[30]

An important consideration is the challenge of moving these promising technologies to real-world application. Potential barriers include sustained funding to support transition from concept to clinically deployable product, as well as the steep regulatory hurdles to move new clinical technologies forward. Further, initial planning around limited invasiveness and high portability is necessary to allow for any meaningful prehospital or field application in either a military or civilian setting. Getting relevant stakeholders together to achieve consensus on the best path forward and garner funding priorities to support promising technologies is a key aspect with precedent.[31] Considering innovative ways to fast-track promising technologies through regulatory processes while still maintaining the necessary safety standards is necessary to ensure life-saving innovations come to deployment in a practical timeline as suggested by the National Academies of Sciences, Engineering, and Medicine (NASEM) in the National Trauma Care System Report.[32]

Question 2 (table 2) led to discussion again emphasizing the importance of immersion experiences in the hospital and trauma centers for prehospital clinicians so that both hospital-based clinicians and medics can learn from each other. An example was given of a 'phases of care conference' in which prehospital clinicians start by presenting the patient from dispatch through transfer of care. Each level of care presents their phase, including referring hospitals, the trauma center, and rehabilitation specialists. Given the rapid pivot to virtual conferencing through the COVID-19 pandemic, this format is ideal to bring multiple care partners together to learn from each other.

The panelists thought a balance was needed in response to question 3 (Table 2). There are some hospital-based capabilities that have already been successful in moving into the prehospital space to improve outcomes, such as blood products and now whole blood.[33 34] However, the right balance of hospital-based clinicians and therapies is critical to identify those that are going to make a difference in patient outcomes but not waste time and resources, especially in austere military or rural civilian settings. Given the challenges of the prehospital environment, they thought more novel technological solutions are necessary to enhance diagnosis and triage.

In concluding with question 4 (table 2), the panelists saw an opportunity to partner with industry to focus on decreasing size, weight, and power requirements to take these advancements into the field. Engineering opportunities to ruggedize as well as streamline and automate interfaces are necessary to make new technologies feasible in a field environment. Solutions to increase the capacity of current ambulance and evacuation platforms were also thought to be a step in the right direction to facilitate prehospital advances in care technology. The panelists thought that partnering with industry is a concrete and necessary step overall to push technologies forward in the prehospital arena to meet the needs of both military and civilian clinicians with iterative improvements and refinement.

CONCLUDING THOUGHTS

The HERETIC prehospital trauma care panel identified several promising education and technology breakthroughs that could substantially improve the prehospital care of injured patients (table 3). Many of these technologies exist but require further advancement to be feasibly and reliably deployed in a prehospital or combat environment. The panel discussed both diagnostic and therapeutic technologies, as well as shifting educational and training paradigms, particularly clinical immersion experiences for prehospital clinicians. Advancing prehospital diagnostics may be important not only to allow more targeted applications of therapeutic options, but also to identify patients with less urgent injuries that may not need more advanced diagnostics, interventions, or transfer to a higher level of care in resource-constrained environments. Academia and industry should partner and prioritize some of the promising advances identified with a goal to prepare them for clinical field deployment to optimize the care of patients near the point of injury. As the NASEM National Trauma Care System Report recognized, prehospital care is an integral component to the care of the injured patients rather than just a ride to the hospital, and a strong military–civilian partnership is necessary to move the needle forward in prehospital trauma innovations.[32]

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ORCID iDs
Joshua B Brown http://orcid.org/0000-0002-6936-035X
Martin Schreiber http://orcid.org/0000-0002-4430-6779

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