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CHALLENGES AND POSSIBILITIES IN FORWARD RESUSCITATION

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ABSTRACT—The environmental and logistical constraints of the prehospital setting make it a challenging place for the treatment of trauma patients. This is perhaps more pronounced in the management of battlefield casualties before extraction to definitive care. In seeking solutions, interest has been renewed in implementing damage control resuscitation principles in the prehospital setting, a concept termed *remote damage control resuscitation*. These developments, while improving conflict survival rates, are not exclusive to the military environment, with similar situations existing in the civilian setting. By understanding the pathophysiology of shock, particularly the need for oxygen debt repayment, improvements in the assessment and management of trauma patients can be made. Technology gaps have previously hampered our ability to accurately monitor the prehospital trauma patient in real time. However, this is changing, with devices such as tissue hemoglobin oxygen saturation monitors and point-of-care lactate analysis currently being refined. Other monitoring modalities including newer signal analysis and artificial intelligence techniques are also in development. Advances in hemostatic resuscitation are being made as our understanding and ability to effectively monitor patients improve. The reevaluation of whole-blood use in the prehospital environment is yielding favorable results and challenging the negative dogma currently associated with its use. Management of trauma-related airway and respiratory compromise is evolving, with scope to improve on currently accepted practices. The purpose of this review is to highlight the challenges of treating patients in the prehospital setting and suggest potential solutions. In doing so, we hope to maintain the enthusiasm from people in the field and highlight areas for prehospital specific research and development, so that improved rates of casualty survival will continue.

KEYWORDS—Remote, damage control, shock, oxygen debt, hemorrhage, blood, airway

INTRODUCTION

The greatest advances in military trauma care over the last decade of war are largely based on a rediscovery of principles and practices from previous conflicts. These protocols include the use of tourniquets and blood product resuscitation for casualties with significant blood loss or uncontrolled hemorrhage. With the changing nature of threat across the globe, our current approach to warfare is more reliant on sophisticated and asymmetric methods, including the greater use of Special Operations Forces in more austere environments. This has created challenges for the management of battlefield casualties before extraction to definitive care and has renewed our interest in implementing damage control resuscitation (DCR) principles in the prehospital setting. These developments, while improving conflict survival rates, are not exclusive to the military environment. Similar situations also exist in the civilian setting, such as motor vehicle collisions in remote areas, casualties entrapped in vehicle wreckage, or an injured climber on the mountainside. After more than 10 years of current international conflict, we are once again seeing a sharing process between military and civilian emergency medical systems: one that continues to help shape the clinical practice of trauma care.

Damage control resuscitation is a systematic management approach designed to minimize blood loss, maximize tissue oxygenation, and optimize outcome. In the last decade, it has become an integral part of battlefield casualty treatment and level I civilian trauma care (1). Acknowledging that 90% of battlefield casualties still die before reaching a medical treatment facility has led some countries to push DCR forward of the surgeon and into the prehospital setting, an approach termed *remote damage control resuscitation* (RDCR) (2). Hemorrhage continues to be the leading cause of death on the battlefield, remains a leading cause in civilian trauma, and poses more of a challenge in the remote setting (3–5). No matter when or where the next conflict is, the use of far-forward tactical strategies will continue, and thus the challenges associated with RDCR will continue.

For both military and civilian environments, a combination of the rediscovery of certain physiological principals, combined with new technology and equipment development, will be required in order to ensure the greatest chance of casualty survival. In this review, we aim to highlight the challenges of treating patients in the prehospital setting and suggest potential solutions. A summary of these can be seen in Table 1.

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Table 1. **Challenges and potential solutions in RDCR**

Challenges	Potential solutions
Environmental conditions	
• Cold/heat	• Protocols and guidelines specific to the prehospital environment
• Light/darkness	• Equipment designed for environmental conditions
• Weather	
• Ongoing threat	• Early evacuation from threat area
Logistical constraints	
• Weight/space	• Equipment and monitoring designed to be light, probable, robust, weatherproof
• Storage	• Guidelines adjusted depending on length of time spent in prehospital phase of resuscitation
• Timelines	
Assessment and monitoring of shock	
• Oxygen debt	• Further research into pathophysiology of shock, including oxygen debt concept
• Measurement	• Further research into the use of serial lactate measurements, and oxygen debt calculation, in trauma
• Reversal and repayment	• Development of point-of-care monitoring for the prehospital environment
	• Research and development of novel technologies such as near infrared spectroscopy
	• Development of newer signal analysis and artificial intelligence techniques
Hypotensive resuscitation	
• Knowledge gaps	• Further research to determine physiological and clinical effects in terms of pressure and time limits
• Technology gaps	
• Pressure targets	• Studies to identify efficacy of hypotensive resuscitation
• Time limits	
• Diagnosis of ongoing hemorrhage	• Imaging and technology development for identifying ongoing hemorrhage in prehospital patients
• Use in TBI	
	• Research and studies for evaluation in TBI
Volume resuscitation	
• Military & civilian practice	• Acceptance that military and civilian practices need different approaches
• Whole blood	• Development of whole-blood programs and protocols
• Other blood products	• Research into other blood and artificial products
• Colloids/crystalloids	• Studies and research into most appropriate fluid for volume resuscitation within the constraints of the prehospital setting
Airway and ventilatory management	• Understanding of physiological consequences of anesthetic agents, laryngoscopy, and positive-pressure ventilation
• Spontaneous vs. mechanical ventilation	• Need for comprehensive training
• Drug-assisted intubation	• Standardized and appropriately equipped service
• Tension pneumothorax	• Rigorous governance structure

The physiology of shock

Any new or reapplied approach or technology that addresses the casualty at risk from continued hemorrhage, before definitive surgical hemostasis, should have as its foundation how it addresses the principles of shock.

Shock occurs when the delivery of oxygen (Do_2) does not meet the metabolic or oxygen consumption (vo_2) needs of the tissues (6). As can be noted in Figure 1, Do_2 (the product of arterial oxygen content and cardiac output) can decrease, whereas vo_2, and thus aerobic metabolism, remains unchanged. This can occur because tissues usually enjoy luxury perfusion, with a decrease in perfusion being countered by an increase in oxygen extraction. This in turn is reflected by a decrease in venous hemoglobin oxygen saturation (svo_2). However, in the continuously hemorrhaging casualty, this state of delivery independent vo_2 eventually turns into a delivery dependent state. At this critical Do_2 level, tissue begins to become ischemic and convert to anaerobic metabolism. Systemically, this is detected by increasing levels of circulating lactate.

Whereas this definition is generally well known among providers of trauma care, the biology and language of its quantification are less well known. This is unfortunate because the science behind this nomenclature and its implications on morbidity and mortality have been known since the early 1960s (7). Oxygen deficit is the degree (in magnitude and time) of vo_2 that tissues spend below that necessary to support aerobic metabolism (i.e., are in anaerobic metabolism). When oxygen deficit is cumulated over time, the level of oxygen debt can be determined (6). In this context, oxygen debt can be understood as the ongoing quantifier of the degree of shock.

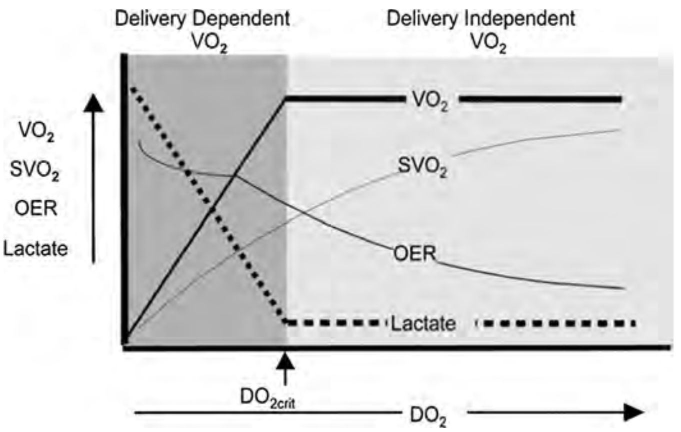

FIG. 1. **The biphasic relationship of oxygen delivery and $\dot{V}O_2$.** OER indicates oxygen extraction ratio.

Oxygen debt has been correlated not only with mortality but also with the complications of shock such as inflammation, coagulopathy, and multiple organ failure (6). This is likely due to a level and burden of global tissue hypoxia that produces a primary injury to the endothelium. Further exacerbation likely results from reperfusion injury, and its associated inflammatory complications, upon resuscitation (8, 9).

Accumulation of lethal levels of oxygen debt will result in irreversible shock (7). Experimentally, in both humans and animals, the measurement of oxygen debt has been made using indirect calorimetry using metabolic carts (10, 11). In routine clinical practice and particularly for the trauma patient, this is not possible, because baseline VO_2 will not be known. Thus, the accurate measurement of real-time oxygen debt has yet to be realized. What is also not well appreciated is that it is not enough to simply halt the accumulation of oxygen debt: it must be repaid. The timing and degree to which oxygen debt is repaid are the key to survival and mitigation of organ failure (6, 10, 12).

Understanding the physiology behind shock is perhaps even more crucial in the context of RDCR in austere conditions, where time to definitive care is prolonged and severe logistical constraints exist for resuscitation therapeutics. These physiological definitions and concepts should drive refinement of RDCR practices. They should lead to hypotensive resuscitation being delivered in a more balanced way and influence development of new resuscitation therapeutics and diagnostics to prevent accumulation of lethal levels of oxygen debt.

Assessment and monitoring of shock

Traditionally, shock has been both diagnosed and quantified using measurements such as estimated blood loss volume, patient vital signs (i.e., blood pressure, pulse, and level of consciousness), and hemoglobin levels (13). Many of these markers are still used currently, especially in forward locations. Unfortunately, these parameters are frequently late changing and subjective (such as pulse quality) and can be confounded by other issues such as decreases in conscious level with an evolving traumatic brain injury (TBI) or analgesia administration. As importantly, variations in physiological reserve make it impossible to use them for estimating or tracking oxygen debt (7). Other tests that assess biochemical markers of anaerobic metabolism are used in an attempt to quantify oxygen debt. Experimentally, serial lactate levels have been used to derive oxygen debt in animals, but as yet not in human trauma patients. However, similar serial type measurements have been used in human sepsis (termed *lac-time*), with the area under the curve being calculated to reflect the degree of oxygen debt and the likelihood of death or subsequent development of multiorgan failure (14, 15). As such, point-of-care lactate monitoring is frequently used in the trauma patient, including in the prehospital setting, and is being shown to have value in predicting the need for intervention (16).

Similar to the challenges of quantifying oxygen debt, monitoring its repayment is difficult. Use of lactate clearance does not guarantee repayment because a return of oxygen delivery to a critical level necessary to support aerobic metabolism will decrease lactate production, allowing lactate to be cleared though normal metabolic pathways. However, oxygen delivery may not be sufficient to pay back the debt to levels necessary to prevent death and multiorgan failure (4, 12).

Our ability to clinically measure oxygen debt in real time has been handicapped by gaps in technology (6). The challenges of monitoring a casualty forward of a medical treatment facility are immense and should not be underestimated. Any strategy designed to optimize RDCR needs an accurate method to both diagnose shock and track improvements with treatment. Technologies and approaches designed with the logistical uniqueness of the RDCR environment should be developed that attempt to determine where the casualty is on the curve in Figure 1. Although it is not possible to provide a comprehensive discussion on all possible technologies here, there are several that could be adapted in the future for such use. One such combination is described in this article.

Several noninvasive spectroscopy techniques, either commercially available or in development, such as near infrared spectroscopy, are capable of measuring tissue hemoglobin oxygen saturation (StO_2) (17). The measure of StO_2 by these technologies is distinctly different from that of arterial hemoglobin oxygenation made by pulse oximetry. Tissue hemoglobin oxygen saturation provides an aggregate measure of hemoglobin oxygen saturation within a volume of tissue. Physiologically, tissue blood volume is heavily dominated (70%–80%) by venous blood (18). Thus, StO_2 is largely a measure of tissue VO_2 and could be used in a manner similar to systemic central or mixed venous saturation as a continuous measure of the adequacy of oxygen delivery. There are currently no clinical studies reporting the use of StO_2 as a hard end point to resuscitation. However, based on the physiological principles of the technology, if coupled with available point-of-care lactate measurement, it may be possible to know if the casualty had passed, or was close to passing, critical DO_2 and was accumulating oxygen debt (6).

By measuring lactate clearance and StO_2, it may also be possible to guide resuscitation and push the casualty just above critical DO_2 or beyond. Tissue hemoglobin oxygen saturation responds rapidly to changes in perfusion, allowing more real-time monitoring and a chance to avoid states of oxygen debt by recognizing decompensation earlier than traditional vital signs

(19). This approach also helps take into account the differences in physiological reserve between individuals. The use of serial lactate monitoring could also be valuable in the triaging of casualties and decision making, particularly in the mass casualty setting. As an example, a casualty with a lactate of 10 mM for more than 3 h would not be expected to survive. By using these technologies, scarce resuscitation supplies could be better utilized.

As indicated above, it is important to repay oxygen debt, although this will be difficult, if not impossible, to do with RDCR. In this setting, with proper technology, the aim would be to limit the accumulation of oxygen debt to ensure that less needs to be repaid. It is unlikely that resources, especially blood products, will be available for complete shock reversal of the severely hemorrhaging casualty in the prehospital setting. Perhaps the ultimate therapy in this regard will be the development of pharmacological agents that significantly reduce tissue vo_2, making it possible to reset critical Do_2 and allow tissues to survive longer at lower Do_2 levels.

While vital signs are known to be a poor marker of perfusion and shock, it is, however, acknowledged that some level of critical perfusion pressure is required to sustain vital organs such as the heart and brain. Consideration should therefore be given to the development of small and robust methods of continuously monitoring if the casualty has dropped below a critical systolic blood pressure (80–90 mmHg). The use of pulse oximetry in conjunction with a blood pressure cuff has been demonstrated to accurately measure systolic blood pressure (20). The combination of pulse oximetry distal to a blood pressure cuff inflated to 80 mmHg could assist the provider in knowing if systolic blood pressure had dropped below 80 mmHg because the plethysmograph would be lost at that time. While accepting that there are limitations to plethysmography in the austere environment, where trauma patients frequently have cold extremities making readings potentially less reliable, a connected combination of these technologies with feedback and automation could easily be envisioned as a significant evolution over pulse quality.

Other technologies based on tissue carbon dioxide physiology, skin perfusion, and temperature may also be of value (17). Use of newer signal analysis and artificial intelligence techniques may provide more sophisticated continuous methods of monitoring capable of assessing multiple casualties (21–23). Sensors that continuously examine parameters such as heart rate variability, plethsymography, and heat flux from the skin could be integrated to produce such a monitor. Only improved research and development in these areas will result in the data and technologies needed to advance RDCR.

Hypotensive resuscitation

Avoidance of blood pressure normalization in a patient with traumatic hemorrhage before definitive surgical hemostasis dates back to at least the 1940s (24). This is based on the assumption that increasing blood pressure above a critical value in patients with noncompressible hemorrhage may "blow" naturally formed clots at the site of injury, resulting in increased hemorrhage. Within the US military, this approach is now part of the current combat casualty care doctrine for the combat medic (25) and is also integrated into guidelines in many other countries.

Unfortunately, all clinical data supporting its use come from civilian studies where time from injury to definitive surgical care is very short, higher ratios of medical personal to wounded are present, and monitoring options are enhanced (26–29). Because only 8% of casualties have any prehospital vital sign documented and only 6% have any documentation of intervention, its success as practiced by limiting volume resuscitation so that systolic blood pressure does not exceed 80 to 90 mmHg is unknown (30). Furthermore, using mental status and pulse quality as a marker of these blood pressure ranges in such austere environments has even less supportive data (31).

Knowledge and technology gaps continue to exist that prevent proper execution and widespread use of hypotensive resuscitation and indeed any other resuscitation strategy considered for RDCR. By its very nature, RDCR was developed as a concept in response to the challenges faced when significant delays in the provision of definitive surgical hemostasis are expected. It is therefore very different from traditional civilian delivery of prehospital trauma care. Hypotensive resuscitation principles have previously been described as potentially beneficial in war and demonstrated to be favorable in modern civilian practice (24). When viewed in the context of the physiological principles of shock and oxygen debt discussed above, it is clear that there will be limits to the use of such strategies in the setting of prolonged field care and RDCR. While delivery of a live casualty to the surgeon is the first prerequisite of survival, delivery of one who has accumulated a lethal level of oxygen debt will be an exercise in futility, and one in which limited resources may have been better used elsewhere.

Because the practice of hypotensive resuscitation assumes the presence of, or high potential for, ongoing hemorrhage, the development and utilization of technologies such as ultrasound suitable for the RDCR setting would seem advisable. This imaging modality is already utilized in some civilian prehospital care systems (particularly the Helicopter Emergency Medical Services). As an example, the casualty who has had a traumatic amputation and significant blood loss who is hypotensive despite the hemorrhage from the amputation being halted with the use of a tourniquet could be viewed as at risk for intra-abdominal hemorrhage. However, practicing hypotensive resuscitation in this casualty would not be warranted if it were possible to be reasonably assured that intra-abdominal or other noncompressible hemorrhage were not present. This would avoid needlessly underresuscitating the casualty and reduce the chances of accumulating complicating or lethal levels of oxygen debt. Additional complexities that exist in attempting to implement hypotensive resuscitation strategies in the polytrauma patient include the presence or potential for TBI, where secondary insults from hypoperfusion and hypoxemia are known to worsen outcome (32). With regard to hypotensive resuscitation, the minimum level of systolic blood pressure that would guarantee an adequate cerebral perfusion pressure remains unknown. In the setting of severe TBI, it is probably best to assume partial or total loss of autoregulation and maintain a mean arterial pressure of between 80 and 100 mmHg. Using only systolic pressure to guide brain perfusion therefore has little basis as a practice.

Whole-blood resuscitation

It is paramount that any resuscitative intervention is "fit for purpose." Within the military setting, it must be recognized that medical field care is different from the civilian urban setting. Although this seems obvious, as in previous conflicts, civilian procedures must be "unlearned," and military medical practice reformed to fit the tactical situation (33). Similarly, despite favorable survival odds, procedures and processes performed within the military setting should not necessarily be universally used in civilian practice. Ideally, prehospital hemorrhagic shock should be treated universally, but because of aforementioned reasons, protocols representing the standard of care in the military setting might be considered substandard in the civilian world.

An example is the use of whole blood by some countries' military forces at forward surgical locations and combat support hospitals. Medical doctrinal support is needed to allow the use of whole blood to facilitate RDCR in austere environments where supply of blood component therapy is either difficult or impossible. To our knowledge, the only guidelines currently supporting the use of whole blood in the prehospital setting are the Tactical Combat Casualty Care guidelines for tactical evacuation care (25). Guidelines for hemorrhagic shock resuscitation at point of injury, before evacuation, are still in favor of colloid-based shock resuscitation. This is based mainly on logistical principles of weight and the maintenance of intravascular volume, at least in the short term, with colloids when compared with crystalloids. This remains a contentious issue as there are conflicting data for improved survival, and concerns remain about the safety of colloids, especially the hydroxyethyl starches (34). Development of other blood products continues to be an area of research and debate. Frozen red cells and "artificial" blood products (e.g., PEGylated bovine hemoglobin and other unencapsulated hemoglobins) may have therapeutic value in restoring tissue oxygenation, but have severe storage limitations for RDCR and will not fully address the loss of clotting factors.

The main reasons for the obvious and ongoing skepticism to whole-blood use are the risks of ABO incompatibility, transfusion-transmitted diseases (TTDs), graft-versus-host disease, and reduced exercise tolerance in donors. However, like many management strategies, the use of whole blood (both fresh drawn and cold stored) is not new; whole-blood transfusion was the standard of forward shock resuscitation in World War II, Korea, and Vietnam. Unfortunately, the current need for fractionated blood components has completely suppressed the knowledge and previous experience gained on the use of whole blood, and a revisit to these old principles seems appropriate.

One of the main differences now is the general perception that type O whole blood is not universal. This is in great contrast to the extensive experience and of its use during the previous wars. Currently, if whole blood is to be used, the recommendations are that it is ABO compatible and should not be cold stored (35). It is accepted that plasma of type O whole blood contains anti-A and anti-B antibodies that increase the risk of hemolysis in the recipient when used universally. However, by choosing donors with a low titer of anti-A and anti-B, this risk is significantly reduced (36). The use of universal low-titer type O whole blood also reduces the risk of fatal ABO incompatibility reactions by avoiding the risk of administering wrong type blood, especially in chaotic emergency situations (37). Similarly, the general assumption that platelet hemostatic function is reduced in association with cold storage needs addressing (38). Although the long-term survival of cold stored platelets once administered is significantly reduced compared with platelets stored at room temperature (38), the relevance of this in the acute bleeding scenario is less important.

The risk of TTD will always be a concern when fresh whole blood (FWB) is used in combat scenarios using on-scene donors and is discussed in detail elsewhere in the supplement. However, it is clear that the benefits of any intervention must always be weighed against the associated risks relevant to that particular situation, and agreement of what is "acceptable" risk is imperative. Another concern is the inherently unsterile field conditions that are presumed to increase the risk of bacterial contamination of the blood. There is no scientific evidence to support this concern, and currently used field protocols use "best practice" infection control measures. Although these risks are real and should not be underestimated, current evidence suggests that the problems can be minimized by thorough planning and training of personnel (39). In approximately 10,000 FWB transfusions to US personnel during Operation Iraqi Freedom and Operation Enduring Freedom (Afghanistan), there have been only two recorded complications of survivable TTD (1 hepatitis C and 1 human T-lymphocyte virus seroconversion) and one fatal case of graft-versus-host disease (40). Despite this use, FWB is not Food and Drug Administration approved, whereas cold stored whole blood is approved for storage for up to 21 days.

For FWB administration to be as safe and efficient as possible, protocols and equipment have to be simple and streamlined to assist the medical provider in far-forward or austere conditions. Although the mission profile for any far-forward special operation will drive equipment requirements, ultimately weight and space restrictions will determine what is achievable, especially when all equipment needs to be carried on the person. As an example, a liter of crystalloid solution weighs approximately 1 kg, whereas a single unit blood collection bag and administration kit weighs less than 200 g. This type of weight saving, while potentially providing superior resuscitative options, is important and highlights the need for further research and development in equipment for the prehospital environment. The specifications of equipment for this environment are quite different from those for in-hospital use and must take into account durability, simplicity, and, if required, a simple and universal power supply.

Reduced exercise tolerance after whole-blood donation is assumed, but not proven, to put the donors at risk in combat situations. Few reports exist on exercise tolerance immediately following whole-blood donation, with most available studies being based on athletes performance 24 h or more after donation (41). A study among Special Forces soldiers measuring exercise performance immediately (in minutes) after the donation of 1 unit of whole blood (450 mL) found no reduction in exercise performance to support this assumption (41). As this study was conducted under "ideal" conditions, a further donor performance study was conducted after a strenuous field exercise. This study, which is pending publication, once again showed no concerning reduction in exercise tolerance among well-trained Special Forces soldiers.

The use of FWB is not purely in the domain of the military. In Bergen, Norway, contingency planning for catastrophes includes the use of FWB in the event that blood products (especially platelets) run out. Leukoreduced whole blood (type O with low anti-A and anti-B titers) would be available using a predefined and tested donor panel supplementing the regular donor pool. Although this may seem too ambitious and unnecessary, terror attacks toward large congregations of people are real and would potentially place unachievable demands for blood on the regular system.

Much of the resistance to the use of FWB can be attributed to the perceived risks associated with its use. However, compared with other accepted lifesaving interventions (LSIs) in the prehospital environment, it is much safer. Fresh whole blood use is unlikely to ever reach the complication rate associated with other LSIs such as surgical airways (42), endotracheal intubation by paramedics (43), or needle decompression for tension pneumothorax (44).

The combination of previous and recent experience and research suggests that there is a place for whole blood in the prehospital setting for selected patients. It would appear that it also carries an acceptable risk profile considering that the mortality rate of hemorrhagic shock in this setting is substantial (45). In the remote setting, where extraction times are long and resources are scarce or nonexistent (particularly blood products), the use of FWB or in-theater predrawn cold stored whole blood may be the only feasible option. This is potentially true for both military and civilian environments; however, more research is clearly needed.

Airway and ventilatory management in shock

Advanced airway management and ventilatory support are generally regarded as vital in the management of patients with major trauma and may be critical interventions in the prehospital setting (46). Indications for drug-assisted intubation (DAI) include airway or respiratory compromise, unconsciousness, combative head injury, humanitarian considerations, and anticipated clinical course. However, there continues to be a lack of clear evidence to suggest that DAI in the prehospital setting is beneficial (47). A Cochrane systematic review from 2008 concluded that "the efficacy of emergency intubation as currently practiced has not been rigorously studied" and that "the skill level of the operator may be key in determining efficacy" (48).

There are many factors unique to the prehospital environment that may make DAI more difficult. Among others, these include restricted patient access, lack of skilled help, limited equipment, poor lighting, excessive noise, and other challenges of the combat or hazardous operating environments. Even with a well-trained, standardized, and resourced service, these contribute to a higher incidence of a difficult airway and complications associated with DAI compared with those performed in hospital (49, 50). Provider competence is a major factor in the delivery of safe airway management, both in-hospital and in the prehospital setting. This can be addressed with adequate training and education; however, the high degree of proficiency needed to be able to perform with high success rates under arduous operating conditions is challenging (51, 52). Furthermore, the ability to "predict" a bleeding trauma patient's clinical course in the field and be able to anticipate the impact of anesthesia and positive-pressure ventilation on the patient's already compromised circulation is extremely challenging (53).

The airway management and respiratory support in a trauma patient require a carefully considered approach according to the individual circumstances. Hypoxemia from either airway or respiratory compromise will potentially lead to a mounting oxygen debt. However, it must also be anticipated that hemodynamic deterioration may occur with intubation and positive-pressure ventilation: Loss of sympathetic tone secondary to anesthetic drugs and increased intrathoracic pressure from positive-pressure ventilation that leads to a decrease in venous return and cardiac output are the main causes. Further reductions in cardiac output can occur if the patient generates auto–positive end-expiratory pressure, leading to dynamic hyperinflation of the lungs. This is seen in both spontaneously breathing and mechanically ventilated patients when the expiratory time, either through tachypnea or an inappropriately set ventilator, is too short to allow for the lungs to return to functional residual capacity. In the critically hypovolemic patient, any increase in intrathoracic pressure may be fatal unless measures are instigated to ameliorate this.

There are also potentially deleterious sympathetic responses to laryngoscopy, even in the hypovolemic patient. These can lead to hypertensive episodes that in turn may have a negative effect on both bleeding and TBI (54). Repeated laryngoscopic attempts not only increase the rate of adverse airway effects but also make the hazardous hemodynamic effects more likely (55). Non–drug-assisted intubation is not advised in trauma patients, and surgical airway (military providers) or supraglottic devices (civilian providers) are now being more frequently recommended for nonspecialist providers in the field.

To avoid delay in getting the uncontrolled bleeding patient to the surgeon, only essential LSIs should be performed before transfer and, if feasible, should be carried out en route. Keeping the patient spontaneously breathing will prevent some of the negative hemodynamic effects stated above; however, we must continue to recognize and address hypoxemia, particularly in patients with TBI. A horizontal approach to resuscitation, with simultaneous control of hemorrhage, fluid resuscitation (preferably with blood products), and administration of prohemostatic drugs, is therefore essential if the decision is made to secure the airway with DAI. The decision to intubate or not requires careful consideration and must take into account the patient's condition, available resources, and timelines to hospital (56).

Whereas hemorrhage and airway compromise are the leading causes of death in the trauma setting, the development of a tension pneumothorax can cause considerable morbidity and mortality and can be difficult to diagnose (57). A pleural air leak leading to a pneumothorax will tension if the defect causing the leak acts as a one-way valve. Speed of development is dependent on the degree of air leak and will be worse if the patient is positive-pressure ventilated or submitted to hypobaric conditions, such as high-altitude MEDEVAC. Physiological deterioration is also different according to their mode of ventilation. In the spontaneously breathing patient, this is likely caused by progressive hypoxemia from respiratory compromise as the lung collapses, leading to eventual respiratory arrest. Conversely, in the ventilated patient, many of the compensatory mechanisms will be reduced or lost, leading rapidly to cardiorespiratory collapse from hypoxemia, reduced blood flow through the collapsed lung, reduced venous return, and possible compression of the great vessels and heart.

The diagnosis is often difficult, and more so in the prehospital setting. The widely described signs and symptoms of chest hyperexpansion and hyperresonance, tracheal deviation, and distended neck veins are seldom seen. More commonly, the patient will be in respiratory distress, tachycardic, and complaining of chest pain, with decreased air entry on the affected side. However, all of these could easily be attributable to other causes, especially in a patient with polytrauma. Diagnosis can be aided with imaging, with ultrasound showing promise (58).

Treatment should be considered if a tension pneumothorax is diagnosed, or considered, and deterioration in cardiac or respiratory function continues. If possible, spontaneous ventilation should continue, because anesthesia and subsequent ventilation may cause some of the compensatory mechanisms to be lost and speed the progression of the tension pneumothorax. Many treatment guidelines (25, 59) advocate the use of needle decompression, although studies have shown this to have a high failure rate, perhaps as high as 65% (44). Chest drain insertion is an option, although it can be technically difficult and time consuming, with the potential for tube blockage and misplacement. If the decision to mechanically ventilate is made, then an open (or finger) thoracostomy can be performed. This fast, relatively simple procedure has a high success rate and allows the provider to confirm a pneumothorax by passing a finger into the pleural cavity (60). This technique, or one similar, could also perhaps be considered in the spontaneously breathing patient. Placing a one-way valve dressing over an open thoracostomy in such a patient would prevent an open pneumothorax ("sucking chest wound") being formed. This would alleviate the need for a chest drain while potentially having a higher success rate than needle decompression. Alternatively a stiff, small-bore tube could be inserted with blunt dissection (or perhaps even a Seldinger technique) that would maintain the integrity of the tract better than a decompression cannula, while not allowing air to be entrained because of its size. Work is needed to determine the best option.

SUMMARY

The challenges facing RDCR remain numerous. The constraints of the environment will not change, equipment and technology development need continued investment, and negative perceptions of its utility will remain. However, the potential benefits are significant. With continued enthusiasm from people in the field, ongoing research and development into equipment fit for purpose, new resuscitation therapeutics that promote cell survival, formulation of forward whole blood, and blood product protocols, advances will continue to be made that ultimately lead to an improvement in casualty survival.

KEY POINTS

- The challenges of providing DCR in the prehospital setting are quite different from those found in hospital.
- An understanding of oxygen debt is essential for the management of traumatic shock. Further research is needed for its quantification, monitoring, and repayment.
- While hypotensive resuscitation is an established concept in RDCR, many knowledge and technology gaps continue to exist.
- The use of whole blood in RDCR should be acknowledged as a feasible resuscitation option.
- The decision to intubate and positively pressure ventilate needs a considered approach, with a thorough appreciation of the physiological consequences.
- Ongoing research and development, specific to the prehospital setting, are needed for continued improvement in casualty survival.

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