Military medical revolution: Prehospital combat casualty care

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In an effort to describe periods of profound change in military organization and practice, historians have given us a unique way to classify and describe these developments in a historical perspective. The concept describes advances in the art and practice of combat arms resulting in profound change as "military revolutions" accompanied by supporting "revolutions in military affairs."

Military Revolutions

Murray and Knox[1] equated military revolutions to "earthquakes." These earthquakes forced a fundamental change in society and a state, and the state consequently altered the way it created and projected military power. Murray and Knox recognize five major military revolutions that have had that impact on Western history: the 17th century creation of the modern state and modern military institutions; the French Revolution; the Industrial Revolution; World War I; and, most recently, nuclear weapons and ballistic missile delivery systems. This concept of military revolutions has also carried into the field of military medicine.

Military Medical Revolutions

Throughout recorded history, there have been several profound medical enlightenments that can be seen as revolutions or "earthquakes" in the management of combat wounded (Table 1). With incremental and cumulative advances, the concept of the military medical revolution (MMR) can be defined by the amalgamation of the multiple and progressively complex medical advances defined by the term *revolution in military medical affairs* (RMMA). RMMAs supporting the overall MMR occurred during the American Civil War, World War I, World War II, the Korean War, and the Vietnam War.

MMRs in the past two centuries have been born of multiple advances that form the underpinnings of a true revolution. The American Civil, Crimean, and Franco-Prussian Wars saw the nascent practice of battlefield anesthesia, system of multiple hospitals, nursing care, and antisepsis that, in the aggregate, would meet the definition of the first MMR supported by multiple RMMAs. Subsequent examples of RMMAs supporting the overall MMR (Fig. 1) occurred during the World War I/World War II era and during the Korean/Vietnam War era.[2–5]

Many advances in combat casualty care from the point of injury to rehabilitation in the continental United States were made during the overseas contingency operations in Iraq and Afghanistan within the decade from 2001 to 2011. The prehospital advances categorized as individual RMMAs are shown (Table 2). Many of these RMMAs were directly translated from civilian trauma practice, whereas others were developed by the military and subsequently translated into the civilian injury care environment.

The RMMAs that occurred during the last 10 years of combat casualty care in the realm of prehospital care are detailed in the following sections.

PREHOSPITAL CARE

Tourniquets

For two millennia, tourniquets were the most controversial topic in first aid,[6,7] but now they are not—they are an essential first aid tool on the battlefield. This change from controversial to essential was an RMMA, a new beginning for an old device.

As recently as the war in Vietnam, tourniquet use was sporadic as soldiers were trained that tourniquets were a "last resort" while some military physicians strongly advocated for their use. Neither point nor counterpoint had adequate data to substantiate its claim and published literature largely relied on opinion.

When US forces went to war in Afghanistan in 2001, with the exceptions of a few Special Operation Forces (SOF) units, they went without tactical tourniquets and were trained not to use tourniquets. In 2001, at the onset of hostilities in Afghanistan, none of the other military services had service-wide tourniquet policies or programs in place. As the United States and her coalition partners suffered losses in Afghanistan, attention was redirected to deaths from potentially survivable injuries, especially extremity hemorrhage. Similar to the Afghanistan operational experience, in March 2003 on entry into Iraq, some of the first US military deaths were soldiers who exsanguinated from isolated limb injuries. Subsequently, the US Army Institute of Surgical Research spearheaded efforts to assess tourniquet options that met specific criteria for deployment.[6] In 2004, with growing clinical and testing experience, military medical experts recommended that modern tourniquets be fielded widely to the deployed forces.[6] The US

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TABLE 1. MMR and Supporting RMMAs

MMR	RMMA
Wound care and patient transport, 16–18th centuries	Dressings and abandonment of hot oil (Paré)
	Gunpowder not a poison (Hunter)
	Flying ambulance (Larrey)
	Hospital as a sanctuary (Pringle)
19th century (American Civil War, Franco-Prussian War, Crimean War)	Hospital systems
	Anesthesia
	Antisepsis/sanitation (Lister, Pasteur, Koch)
	Nursing care (Nightingale)
World War I and World War II	Antibiotics
	Blood transfusions
	Dakin's solution
	Positive-pressure ventilation for "wet lung"
	Traction for femur fractures
	FDP
	Mobile far-forward surgery
Korean War and Vietnam War	Renal dialysis
	Helicopter evacuation
	Transcontinental evacuation
	Vascular repair
	Mafenide burn topical
	Identification of acute respiratory distress syndrome ("Da Nang lung")

Adapted from Pruitt and Pruitt[2] (2008).

Special Operations Command (USSOCOM) was the first command to mandate tourniquets for its deploying combatants (USSOCOM Chief of Staff, Tactical Combat Casualty Care Training and Equipment e-mail message, March 5, 2005). By 2006, tourniquet use on the battlefield had become ubiquitous. The combat support hospital at Ibn Sina Hospital (Baghdad, Iraq) was a central hub of medical care in Iraq. At Ibn Sina Hospital, investigators documented the lifesaving impact of prehospital tourniquets with more precision than had ever been accomplished in previous studies. In a comprehensive approach, prehospital emergency tourniquets saved lives when

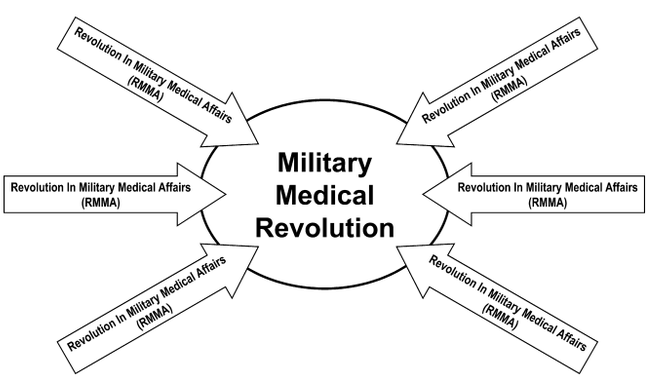

Figure 1. Concept of MMR and RMMAs.

TABLE 2. RMMAs, 2001 to 2011 Overseas Contingency Operations in Afghanistan and Iraq

Overseas Contingency Operation	RMMA
Prehospital care	Tourniquets
	Topical hemostatic agents or dressings
	Hypothermia prevention
	UK MERT Team–prehospital care
	Hypotensive resuscitation
	Prehospital resuscitation with FDP
	Junctional tourniquet

they were used rapidly and correctly in the setting of life-threatening extremity hemorrhage. Comparing data on tourniquet use before- versus after-shock onset, placement prehospital versus hospital, and no tourniquet use versus tourniquet use painted a clear picture of major survival benefit with powerful, scalable, temporal, and physiologically based associations.[7]

Modern tourniquet use has had a far reaching impact and has been responsible for saving an estimated one to two thousand US military lives in Operation Enduring Freedom and Operation Iraqi Freedom. Tourniquets are now perceived as an essential tool for implementing best practice care of war casualties. After aggressive reintroduction, use of the battlefield tourniquet has been the signature lifesaving prehospital intervention of the wars in Iraq and Afghanistan and represents a profound change in prehospital combat casualty care.

Hemostatic Dressings

Hemorrhage remains the leading cause of potentially preventable death among combat casualties. The urgency of this problem led to a revolution in the development and use of battlefield hemostatic dressings. For more 2,000 years, gauze dressings have been used to staunch bleeding. In efforts to improve on this ancient hemostatic dressing, military laboratories developed test and evaluation programs for these products resulting in improved dressings fielded expeditiously to treat life-threatening hemorrhage.

First Generation of Hemostatic Dressings

The US Army's early effort to improve hemostatic dressings focused on the dry fibrin sealant dressing.[8] This dressing was briefly deployed to SOF medics in Iraq but was withdrawn because of regulatory challenges. This agent was replaced with the HemCon bandage (HC). These dressings were widely distributed among US Army forces for use on the battlefield. HC is made of freeze-dried chitosan and works by tissue adhesion and interaction of its positively charged chitosan with negatively charged blood cells.[9] Concurrent with HC fielding by the US Army, QuikClot, a granular hemostatic agent, was deployed by the US Navy and the US Marine Corps. Experimental studies demonstrated efficacy against venous bleeding[10] or mixed arterial and venous bleeding (better than gauze or no treatment at all);[11] however, it was ineffective against a more severe arterial bleeding.[12] The proposed mechanism of this mineral-based (zeolite) agent is through absorbance of water and concentration of blood clotting proteins and cells resulting in hemostasis.[13] The

significant heat generated as a result of interaction of zeolite with blood/water may have also contributed to the hemostatic function, but the heat generated was the source of safety concerns and documented burns.[10,14]

Second Generation of Hemostatic Dressings

The effort to find better hemostatic products and support development of more promising agents continued, and by 2007, a number of new topical hemostatic agents had received clearance from the US Food and Drug Administration (FDA) and were subjected to comprehensive studies in two independent military laboratories.[15–18] Based on an analysis of data from animal models designed to evaluate both safety and efficacy, in 2008, Combat Gauze was recommended by the Committee on Tactical Combat Casualty Care for distribution to US forces. Combat Gauze has now been widely distributed and essentially has replaced the previously deployed hemostatic agents (HC and QuikClot).

Hypothermia Prevention

Hypothermia, defined as a core body temperature of 35°C or less, has been associated with greater resuscitation fluid requirements, prolonged clotting times, and other dysfunctions of the hemostatic process, independent of the development of acidosis following traumatic injury.[19–22] For the military, the hypothermia incidence rate was 6.0%, and hypothermic casualties had a significantly higher mortality rate.[23]

Efforts to prevent hypothermia onset are a challenge in military prehospital settings (US Army Levels I and II), and hypothermia prevention has become a high priority, leading to its inclusion in the teachings of Tactical Combat Casualty Care (TCCC). The wool blanket has a long history but has recently been shown to provide little benefit in preventing heat loss.[24] The consequent innovation was the development of the Hypothermia Prevention and Management Kit (HPMK) to provide warmth for several hours without an external power source. The HPMK includes a reflective blanket with an incorporated hood and four built-in chemical heating elements that are more effective in maintaining body temperature.[24] When the HPMK was combined with a targeted training program and diligent process improvement initiative, the US Military was able to significantly reduce the incidence of hypothermia in combat casualties.

Prehospital Care in the United Kingdom Defence Medical Service

The rapid tactical evacuation (TACEVAC) of military casualties from the battlefield to higher echelons of care is a crucial mission to preserve the life of casualties in critical conditions. TACEVAC includes evacuation by both designated medical (MEDEVAC) mobility assets and casualty evacuation (CASEVAC) by tactical mobility platforms. Helicopter TACEVAC enables relatively rapid, long-range evacuations independent of ground transportation infrastructure. Recognition that severely injured patients can significantly benefit from lifesaving interventions such as damage-control resuscitation (DCR), advanced airway maneuvers, and thoracic trauma management before arrival at a Role 2 facility led to the development of the Medical Emergency Response Team (MERT), a revolution in military medical evacuation (Fig. 2).

The use of physicians and nurses in aeromedical evacuation has its roots in the Incident Response Team used in Iraq, which included an emergency nurse and a doctor when required. This concept was expanded in 2006 in response to the potential, long evacuation times of casualties inherent to UK Armed Forces operations in Helmand Province in southern Afghanistan.[25] The MERT consists of a critical care skilled registered general nurse with emergency medicine background and a paramedic.[26] This team is equipped and trained to provide battlefield advanced trauma life support interventions. This basic MERT format is almost always "enhanced" (MERT-E) with the inclusion of a second paramedic and a senior physician (consultant or very senior trainee) drawn from the emergency medicine or intensive care cadre, enabling physician-led interventions.[27] The MERT is capable of deploying on a variety of platforms, but in Afghanistan, MERT uses a CH-47 Chinook. The CH-47 is capable of carrying up to 8 stretcher cases or 20 ambulatory casualties, and in addition to the MERT, the CH-47 also carries four soldiers who provide force protection and can assist the MERT with basic procedures.

The underlying philosophy is the concept of early critical care that dovetails into the UK Defence Medical Service trauma system paradigm of DCR. The practices of the MERT that facilitate the delivery of this medical doctrine for catastrophic bleeding, airway protection, thoracic trauma management, and other clinical and nonclinical aspects are as follows.

Catastrophic Bleeding

In addition to hemostatic advanced dressings and tourniquets, early hemostatic resuscitation with prehospital blood products is a key component of DCR. The MERT-E carries a cold box containing 4 U of O-positive packed red blood cells (PRBCs) and 4 U of fresh frozen plasma (FFP), and any dispensed blood products are given through a fluid warmer. The decision to transfuse is physician led and is intended for critically shocked patients who are considered salvageable. These

Figure 2. Medical Emergency Response Team.

are difficult decisions that require experience and injury pattern recognition—a theme throughout MERT practice. In parallel with the administration of prehospital blood is the option to administer the antifibrinolytic drug tranexamic acid.[28]

Airway Protection

A skill common to all physicians deploying on the MERT-E is that they must be proficient at airway assessment and competent to definitively secure an airway if required. Generally, this takes the form of a rapid sequence induction using direct laryngoscopy. Several rescue devices are also available as alternatives or for use in a failed intubation such as supraglottic airways, optical laryngoscopes, and cricothyroidotomy.

Thoracic Trauma Management

A large supply of oxygen is carried on the CH-47. This allows the administration of 15 L per minute for all casualties carried if required. Apart from application of a chest seal, the main thoracic intervention practiced on the MERT and MERT-E is the thoracostomy to decompress the chest. A more radical approach to patients in extremis is to perform a prehospital thoracotomy with the aim of releasing a tamponade, controlling hemorrhage, and/or controlling the aorta.[29] Although this facility exists on the MERT-E, few have been performed, with no survivors to date.

Prehospital Resuscitation with Freeze-Dried Plasma

Although the field of transfusion medicine was essentially born on the battlefields of World War I and freeze-dried plasma (FDP) was developed early in the 1940s and extensively used by US Forces during World War II, hemorrhage resuscitation practices strayed widely from the experience of these conflicts, and it is only now that we are developing the scientific evidence to establish prehospital FDP use as an RMMA. Crystalloid was widely used to treat hemorrhagic shock resuscitation during the Vietnam War, and this practice became codified in the Advanced Trauma Life Support teachings developed for civilian trauma systems during the 1970s and 1980s. By the 1990s, it was recognized that this practice had caused a virtual epidemic of dilutional coagulopathy and abdominal compartment syndrome in severely injured trauma patients who were aggressively resuscitated. Early US military experience in Somalia, Afghanistan, and Iraq revitalized the concept of treating hemorrhage with plasma to preserve coagulation system function and treat the acute coagulopathy of trauma as well as to replace physiologic buffers and treat acidosis.

The requirement to keep plasma frozen presents obvious logistical problems for operational military use, particularly during operations in remote and austere environments. An FDP product that would be stable at ambient temperatures and that could be reconstituted for use on demand would permit delivery of plasma to bleeding casualties in the field and reduce suboptimal treatment with crystalloids and colloids. The US military is currently developing such products with commercial partners. While these programs advance toward the goal of approval from the FDA, the USSOCOM has partnered with the French military to field French-made FDP under an expanded access investigational new drug protocol. The French FDP will be used in far-forward operations by SOF medical personnel to treat critically wounded casualties. This French product represents the first step in the long march to restoring FDP to the US trauma care armamentarium after a decades-long hiatus. This concept has been reviewed and endorsed by the Defense Health Board. It is anticipated that this nascent RMMA will result in improved battlefield care and pave the way for a transformation of civilian trauma resuscitation.

Transformations in Military Blood Banking

The wars in Afghanistan and Iraq are the first major conflicts fought by the United States in the modern era of transfusion medicine. At the beginning of the conflicts in Afghanistan and Iraq, the standard blood products available to deployed US military units were PRBCs and FFP. Cryoprecipitate and platelets were unavailable. Military doctrine allowed for emergency use of fresh whole blood (FWB) in combat settings if components were unavailable or if it was thought that a patient would benefit from FWB (e.g., owing to a deficiency of platelets). In 2004, apheresis platelets were collected in Balad, Iraq, for use in combat trauma. The Afghanistan/Iraq war saw the development of the concept of DCR.[30] This led to a significant increase in FFP use and the unprecedented distribution of FFP to the Role 2/Forward Surgical Team setting. Positive results from analyses of platelet transfusion led the Army Surgeon General to mandate availability of apheresis platelets in every Role 3/combat support hospital setting in 2008.[31] US military blood banking practice thus adapted to support the implementation of 1:1:1 (platelet/FFP/PRBC) transfusion across the vast Central Command area of operations. In addition, Armed Services Blood Program Office worked relentlessly to speed delivery of PRBC units to theater so that the average age of such units arriving in theater continued to drop, such that, in 2012 the average age of PRBC units transfused in Afghanistan was 21 days. Interestingly, more than 8,000 U of FWB have been transfused, with data showing improved outcomes when compared with components.[32] Finally, important strides to improve transfusion safety were made for recipients of FWB with the fielding of rapid tests for human immunodeficiency virus, hepatitis B virus, and hepatitis C virus.

Junctional Tourniquet

In an autopsy analysis of 558 US casualties who died of wounds, 51.4% had potentially survivable injuries. Eastridge et al.[33] reported that in the hemorrhage mechanism of potentially survivable cases, 21% had junctional (neck, axilla, groin) bleeding as the dominant mechanism of death.[32] In 2008, Blackbourne et al.[34] made a plausibility case that Lister's tourniquet, which was used in surgery for hemorrhage control, could be used prehospital by medics to control hemorrhage as a next generation of tourniquets. Compared with extremity tourniquets, junctional tourniquets present a greater challenge. Severe junctional wounds are larger, more proximal, and anatomically more complex and involve more associated injuries of greater severity than other wounds.[35] The bleeding is faster, and the intervention is needed more quickly, whereas the vessels are harder to compress.[35]

In response to this challenge, the Medical Research and Materiel Command issued a Request For Information (W81XWH-RFI-003) on March 3, 2010. The Combat Ready Clamp (Combat Medical Systems, Fayetteville, NC) was developed in response. The clamp was approved by the FDA for difficult inguinal bleeds on the battlefield in 2010, and in 2011, the Committee on Tactical Combat Casualty Care voted to recommend the junctional tourniquet, and the recommendation was approved by the Defense Health Board in 2011 (Combat Ready Clamp). As the first devices are fielded in Afghanistan, work continues to assess these devices in theater and in laboratory studies.

CONCLUSION

TCCC divides care into three phases based on the tactical situation. During active hostile threat, attention is focused primarily on eliminating the threat. As the threat decreases, increasing focus is applied to providing the best possible medical care for the casualties. This paradigm of field care in tactical settings is very different from civilian environment. Tactical and environmental factors have a profound impact on trauma care rendered on the battlefield. Good medicine can be bad tactics. These tenets of prehospital care on the battlefield have been revolutionized by the dissemination of the principles of TCCC and have dramatically improved combat casualty outcomes.

AUTHORSHIP

L.H.B. was responsible for the concept and design of this article, compilation of the text, figure and table composition, and extensive reviews. All authors listed contributed a section, with references, in their area of expertise and reviewed the article. In addition, D.G.B. and B.J.E. provided extensive reviews of the article.

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