

Optimizing the use of Limb Tourniquets in Tactical Combat Casualty Care: TCCC

Guidelines Change 14-02

Stacy A. Shackelford, MD; Frank K. Butler Jr., MD; John F. Kragh Jr., MD; Rom A. Stevens, MD; Jason M. Seery, MD; Donald L. Parsons, PA-C; Harold R. Montgomery, NREMT/ATP; Russ S. Kotwal, MD; Robert L. Mabry, MD; Jeffrey A. Bailey, MD

Keywords: Tourniquet, Tactical Combat Casualty Care Guidelines, external hemorrhage control, shock, resuscitation, emergency medical services

Proximate Cause for the Proposed Change

The early use of limb tourniquets has been documented to save lives on the battlefield, but has the potential for significant morbidity. This change has four goals:

1. Clarification of tourniquet conversion guidelines. Since its inception, Tactical Combat Casualty Care (TCCC) has emphasized the early and liberal use of tourniquets to control life-threatening hemorrhage in the Care Under Fire (CUF) phase. Because evacuation times in Iraq and Afghanistan have been relatively short, the recommendation in the TCCC Guidelines to re-evaluate the need for a tourniquet in the Tactical Field Care (TFC) phase of care and use other means of hemorrhage control has been de-emphasized in practice by users. There is often no attempt to convert tourniquets to hemostatic or pressure dressings because of the short evacuation times in Afghanistan at present. Increasingly, worldwide casualty care scenarios are anticipated to include long-range evacuation. Recent real-world events in theaters other than the Middle East have demonstrated that reinforcement of tourniquet conversion guidelines is needed at this time.

2. Clarification of effective tourniquet placement. Ineffective venous tourniquets have been shown to be a relatively common occurrence that increases blood loss and complications.¹⁻³ Optimal use of limb tourniquets must result in both cessation of bleeding and stoppage of the distal pulses in the extremity.
3. Clarification of the location of tourniquet placement during CUF. During a prehospital trauma care assessment in Afghanistan in 2012, inconsistencies relating to tourniquet placement were noted between the TCCC guidelines and actual training in some TCCC courses. In particular, “high and tight” tourniquet placement (also termed “hasty” tourniquet placement) is not specified in the TCCC Guidelines, which call for tourniquet placement “proximal to the bleeding site” in the CUF phase. This update supports placement of the tourniquet “high and tight” (as proximal as possible) on the injured limb during CUF.
4. Review recommendation for Combat Application Tourniquet (CAT) routing of the band through the buckle. Armed Forces Medical Examiner Feedback to the Field #11, Feb 2012 reported a survey of tourniquets recovered from deceased service members. It was found that the standard-issue CAT was commonly placed with the friction band routed once through the buckle (“single slit routing”) in 35% of lower extremity placements and 53% of upper extremity placements.⁴ Previous training and manufacturer’s instructions supported single slit routing only for the upper extremity during self-application.⁵ However, accumulated experience and recent evidence⁶ indicate that single slit routing of the CAT is effective, faster, and reduces blood loss compared to double slit routing.

The TCCC guidelines address junctional tourniquets and limb tourniquets. Junctional tourniquets are identified as such in the text. Otherwise, “tourniquet” refers to limb tourniquets.

Background

The use of a tourniquet as a first aid tool on the battlefield is the foremost advance in prehospital care during the wars in Iraq and Afghanistan, with an estimated 1,000-2,000 lives saved by tourniquet application.⁷ In prior conflicts, prolonged tourniquet use led to limb loss from ischemia; morbidity observed from tourniquet use led to controversy regarding battlefield tourniquets use.⁸ Recent military experience, however, has clearly illustrated that tourniquets can prevent death from limb hemorrhage.^{9,10} Such lifesaving tourniquet use has been realized through careful attention to process improvements aimed at maximizing the benefit while minimizing the morbidity.

The first edition of the Tactical Combat Casualty Care Guidelines¹¹ supported early use of tourniquets to control life-threatening hemorrhage from extremity wounds; such support contradicted longstanding doctrine in which the tourniquet was an intervention of last resort.^{12,13} A decade of concerted effort ensued, with the combined efforts of U.S. Special Operations Command (USSOCOM), U.S. Central Command, U.S. Army Institute of Surgical Research (USAISR), and the Committee on TCCC (CoTCCC) combining efforts to develop the evidence base, doctrine, training, policy and implementation ultimately resulting in the issuing of tourniquets to every deploying service member with training to support immediate application for life-threatening limb hemorrhage. The turning point in tourniquet use occurred in 2005 as the result of three highly publicized articles, 1) a laboratory evaluation of battlefield tourniquets by the USAISR,¹⁴ 2) an internal report later published as an analysis of the causes of death in

special operations forces,¹⁵ and 3) a Baltimore Sun front page newspaper article detailing combat deaths from wounded extremities and the military's bureaucratic inertia in fielding much-needed tourniquets to its troops, culminating in a strong expression of senatorial concern to the Secretary of Defense.¹⁶

Successful use of tourniquets on the modern battlefield resulted from a combination of factors: new and improved manufactured tourniquet designs, laboratory testing of tourniquet effectiveness, and documentation of preventable deaths from extremity hemorrhage early in the conflicts in Iraq and Afghanistan when tourniquets were not routinely issued and improvised tourniquets were not effective. At the onset of hostilities in Afghanistan, only a few selected Special Operations units (Navy SEALs, the Army Special Mission Unit, the 75th Ranger Regiment, and Air Force Special Operations Forces) carried tourniquets, and mandated training and fielding of tourniquets to all of their personnel.¹⁷ Beginning in 2005, service-wide standardized tourniquet training became mandatory throughout the U.S. military, along with fielding of lightweight, easily carried, effective tourniquets to both medical and non-medical personnel alike. Dedicated data collection through approved research protocols and through the DoD Trauma Registry allowed detailed analysis of preventable deaths and certain limb-related outcomes. Such data spurred ongoing process improvements that included five refinements in the CAT's design and four updates to the TCCC guidelines relating to tourniquet use. Also, maturation of the Joint Theater Trauma System and dispersion of medical assets in theater allowed for an average transport time from point of injury to a surgical facility that was under one hour.

Tourniquet-related morbidity has been assessed using available data, however knowledge gaps still remain. Fasciotomy rates increased after implementation of tourniquets, likely due to

increased numbers of lives saved and limbs salvaged, however the relation of fasciotomy to tourniquet use has not been clearly defined and potential for otherwise unnecessary fasciotomy exists, particularly in cases of a “venous tourniquet” which occludes venous outflow while failing to occlude arterial inflow.^{1,18,19} Although studies to date show no increased limb dysfunction or late amputations as a function of prehospital tourniquet use, detailed long-term follow-up studies have not been done.

Due to commonly short evacuation times in Afghanistan after the Secretary of Defense directive for such in 2009, tourniquets have been routinely left in place until the patient is under the care of a surgeon. When evacuation time is long, which is common in immature theaters of conflict and on Special Operations missions, failure to re-evaluate and convert no longer needed tourniquets to hemostatic or pressure dressings may lead to prolonged ischemia and avoidable loss of the extremity. Recently, a casualty suffered a surgical amputation of the lower limb due to a tourniquet left in place during a long evacuation to a local national hospital with a total tourniquet time of 8 hours; upon surgical exploration of the leg, no major vascular injury was found. If the tourniquet had been converted to a hemostatic or pressure dressing during Tactical Field Care (TFC) or Tactical Evacuation (TACEVAC) Care, it would be reasonable to expect that the amputation could have been prevented. This case illustrates the point that the need for a tourniquet must be re-assessed during both TFC and TACEVAC phases of TCCC, at most 2 hours after initial tourniquet placement, and serves as a reminder that vigilance is required to prevent or minimize tourniquet-related morbidity, particularly when evacuation is long or delayed. There have been no known cases of limbs lost to tourniquet ischemia in U.S. casualties of the Iraq or Afghanistan wars, although there were at least two unpublished cases in Afghanistan of limb loss from tourniquets inadvertently left in place for extended periods in

Afghan casualties under Coalition care. These events reinforce the need for awareness that, even in well-established combat trauma systems, communication errors and handoff errors can occur, leading to failure to remove a tourniquet and resulting in avoidable harm. Altogether, the tourniquet evidence in the current war indicates that compliance with the TCCC guidelines by the tourniquet user has been associated with a reduction of morbidity and mortality compared with non-compliance.^{1,19, 20}

With the drawdown of combat operations in Afghanistan, we find ourselves at a transition point in combat casualty care that leads us to develop preparations for future worldwide conflicts. For casualties in future conflicts, we aim not only to maximize survival but also to optimize function. Better documentation and analysis of prehospital care along with improved long-term follow-up will allow more detailed assessment of late complications and limb-related functional outcomes in relation to prehospital tourniquet use.

Discussion

Historic perspective on tourniquet use

Tourniquet use was a controversial topic in first aid for nearly two millennia.^{8,21} The earliest use of tourniquets to control blood loss was associated with surgical amputations, allowing surgeons to perform the procedure with minimum blood loss.²¹ During the American Civil War in 1862, Samuel Gross of the Union Army recommended issuing a tourniquet-like device to every combat soldier along with appropriate training.²² However, criticisms of tourniquet use also occurred during this conflict, often associated with poor outcomes as a result of limited training or prolonged transport time (many hours or even days) to surgical hospitals.

World War I brought the introduction of the battlefield medic, while transport to field hospitals was often delayed. Surgeons often saw the negative effects of tourniquets, and the

prevailing viewpoint was that the tourniquet should be used only after attempting elevation and compression of pressure points, and, as stated in the official British manual of 1918, that “the systematic use of the elastic tourniquet cannot be too severely condemned.”²³

The controversy between the potential lifesaving benefit of the tourniquet and the potential harm persisted through the remainder of the 20th century. Most published opinions, however, were written by surgeons and ignored the fact that casualties who exsanguinated from limb hemorrhage never reached the hospital while those who did survive to reach the hospital experienced complications.

In World War II, Wolff and Adkins reported their observations of tourniquets applied prehospital and offered lessons learned from a year in combat in the Italian theater. They noted that the standard-issue tourniquet of the time, a simple canvas strap with spring-tension buckle, lost tension during placement and was often not effective. The authors strongly advocated for early and effective tourniquets.²⁴

The Korean and Vietnam wars saw the development of helicopter evacuation from the battlefield, reducing the time to reach surgical treatment. The World War II era tourniquet continued to be used despite ineffectiveness, and many tourniquets were improvised.²¹

The 1975 revision of the Emergency War Surgery manual stated “As an emergency measure, until more effective measures can be instituted, external hemorrhage can often be checked by direct pressure...Tourniquets are rarely needed for the control of hemorrhage and should be used only when all other methods fail. A tourniquet properly applied can save life but endanger limb.”¹² This recommendation was repeated in the 1988 revision of the text.¹³

Bellamy’s analysis of Vietnam combat deaths recorded that 9% of KIA exsanguinated from extremity wounds and that 88% of deaths occurred prehospital.²⁵ He noted that “a

substantial number of these casualties exsanguinated from arterial wounds at sites where simple first aid measures (direct pressure, pressure on the cognate artery, or application of a tourniquet) might have been expected to control hemorrhage” and stated that “First and foremost, there is a need to improve the field management of hemorrhage.”²⁶

The modern era of tourniquet use in the U.S. military required a doctrinal change from tourniquet use as a means of last resort to a means of first aid. Experience gained in Special Operations translated into a formal assessment of needs during Tactical Combat Casualty Care (TCCC) and the publication of guidelines in 1996, for the first time formally describing the circumstances of medical Care Under Fire with appropriate guidelines for three phases of prehospital care.¹¹ The tourniquet was the only medical intervention recommended under fire, followed by consideration of tourniquet removal and conversion to hemostatic or pressure dressing to control bleeding under more controlled circumstances during TFC and TACEVAC Care. TCCC, including aggressive use of tourniquets to control life-threatening limb hemorrhage, was incorporated in casualty response programs in the Naval Special Warfare Command in 1997, followed quickly by the Army Special Mission Unit, the 75th Ranger Regiment and Air Force Special Operations Forces.

A formal evaluation of various tourniquets was first published in 2000,²⁷ demonstrating a new commitment to optimizing device performance. In 2003, tourniquet devices were further evaluated for use in Iraq and Afghanistan. Testing at the USAISR found that the Combat Application Tourniquet (CAT), the Special Operations Forces Tourniquet-Tactical (SOFTT) and the Emergency & Military Tourniquet were all effective at stopping distal blood flow in human volunteers.¹⁴ The CAT has since become the most widely fielded tourniquet in the U.S. military, initially by USSOCOM²⁸ and later by the rest of the U.S. military. By 2006, after a decade of

commitment by key advocates to design, test, train, and field battlefield tourniquets, tourniquet use on the battlefield had become ubiquitous.^{7,17} In 2009, Kragh et al demonstrated clearly that for casualties with uncontrolled limb hemorrhage, survival with tourniquet use was higher than without, particularly if a tourniquet was applied before onset of shock, emphasizing that, within the comprehensive military trauma system with effective devices, training, and fielding to all forces, that mortality was improved while morbidity was minimized.⁹

Preventable deaths

Analysis of combat mortality data during the Iraq and Afghanistan wars led to an improved understanding of the potentially preventable causes of combat death and spurred new strategies for medical treatment, training and equipment. A focus on limb hemorrhage in particular provided the data to support widespread implementation of tourniquet use by U.S. forces. An analysis of 82 fatalities in U.S. Special Operations Forces from 2001-2004 showed that 12 (15%) deaths resulted from potentially survivable wounds, including 3 of 12 (25%) with “tourniquetable” hemorrhage.¹⁵ A larger study published in 2008 of 982 U.S. military fatalities showed similar results, with 24% of deaths designated potentially survivable and 33% of the potentially preventable deaths attributed to limb hemorrhage.²⁹

In 2012, Eastridge et al published an analysis of 4,596 battlefield deaths occurring from 2001-2011.³⁰ This largest study reinforced the findings of prior studies, with 24% of prehospital combat deaths designated as potentially survivable. Of the potentially survivable deaths, 91% resulted from hemorrhage, with 12% attributed specifically to limb hemorrhage. This study also focused renewed attention on prehospital interventions since 87% of combat deaths occurred before arrival at a medical treatment facility. A clear decrease in deaths from limb hemorrhage over the course of the war was demonstrated, with 6.7-fold decrease in limb hemorrhage deaths

annually occurring after full implementation of training and dissemination of tourniquets among U.S forces.

Published series on tourniquet use

Battlefield tourniquet use in the modern era has demonstrated a positive risk-to-benefit ratio, shown to save lives with low morbidity. Several series of combat use have been reported.

The Israeli Defense Force experience was reported in a retrospective study of 550 casualties, 91 of whom received a tourniquet. They reported no deaths from uncontrolled limb hemorrhage and a 47% incidence of non-indicated tourniquet placement, based on both tactical and anatomic indications taught in training; 78% of tourniquets were effective (completely stopped bleeding) and neurologic complications occurred in 6.4% of limbs with tourniquet times of 109-187 min.³¹

A retrospective review of all 165 patients arriving at Baghdad's 31st CSH in 2004 with major traumatic amputation, extremity vascular injury or prehospital tourniquet compared casualties with tourniquets applied prehospital and in the emergency department (40% of casualties) to those without tourniquet use (60%). Tourniquet use was associated with improved hemorrhage control in this study. Of note, 18% of tourniquets were non-indicated, 15% were ineffective and another 15% rebled after resuscitation. No tourniquet-related complications were reported. This study, conducted at a time before widespread tourniquet training and distribution to U.S. forces, demonstrated that 4 of 7 deaths might have been prevented with earlier tourniquet use.³²

In 2006-2007, a prospective observational survey (in three time periods) was conducted at a single combat support hospital in Iraq. These reports demonstrated 90% mortality for casualties with tourniquets placed after the onset of shock and 10% mortality for those with

tourniquets placed before shock onset, providing strong support for early tourniquet use.

Ineffective tourniquet placement (persistent bleeding or persistent distal pulses) occurred in 28% of patients. Morbidity in this series was low, with a 1.7% incidence of transient nerve palsy and no amputation directly attributable to tourniquet use alone, although an increase in both amputation and fasciotomy rates was associated with tourniquet use longer than 2 hours. Morbidity assessment was challenging with many associated injuries, and long-term follow-up was absent in these reports. However, the lifesaving benefit of early tourniquet use was clearly demonstrated.^{1,9,10,33}

The 75th Ranger Regiment experience was reported in a retrospective study of 419 casualties, of which a total of 89 limb tourniquets were applied to 66 casualties with no resultant complications. Of these casualties with tourniquets, 95% reached the next level of care alive and 94% ultimately survived. Sixteen percent of these survivors had underlying injuries that resulted in limb amputations, however no amputation was attributed directly to tourniquet use. Additionally, this study noted that non-medical personnel accounted for 42% of tourniquet applications.³⁴

Common themes of the modern combat publications illustrate that early tourniquet use prevents limb exsanguination and saves lives, that non-indicated tourniquet placement is common (even when CUF is included as an indication), and that morbidity is uncommon when tourniquet use is relatively brief. Ineffective tourniquet use remains common, and in one process improvement project published in 2012, 83% of limbs treated with a tourniquet had palpable distal pulses and 74% did not have a major vascular injury; concurrently no major vascular injury presented without a tourniquet.³ This experience further supports that a certain amount of “over treatment”—placement of tourniquets later deemed “unnecessary”—may be needed to

achieve a zero miss rate for exsanguination, however additional emphasis should be given to improving training on tourniquet indications and early conversion to hemostatic or pressure dressing in the field.

Indications for tourniquet use

TCCC guidelines specify that tourniquets should be applied for life-threatening external hemorrhage that is anatomically amenable to tourniquet application, the only medical intervention recommended during CUF.³⁵ Due to tactical priorities during the CUF phase which override those of routine, non-tactical medical care, the capacity for assessment and treatment is limited and tourniquets may be placed aggressively to prevent exsanguination.

Other published indications for tourniquet use include situational indications such as mass casualty events, total darkness, and situations where the patient requires an airway or breathing intervention. Anatomic indications also include arterial hemorrhage and traumatic amputation above the wrist or ankle.^{31,33,36}

In a prospective observational survey of 728 casualties with 953 limb injuries, indications for tourniquet placement were categorized by amount of hemorrhage, anatomic indications, and situational indications. Of these, 51% had major hemorrhage and 49% had minor hemorrhage. The most common anatomic indications for tourniquet placement were open fracture (27%), traumatic amputation (26%), soft tissue wounds (20%), and vascular injuries (17%). The most common situational indication for tourniquet placement was bleeding from multiple sites (61%); it was stated that CUF and other situational indications for tourniquet placement were under-reported in this survey.³³

The CoTCCC recommends tourniquet placement for life-threatening hemorrhage, including suspected life-threatening hemorrhage that is not fully assessed during CUF, multiple

casualty situations, or multiple injuries requiring intervention in a single casualty, and for all major amputation injuries.

Recommendations for conversion of tourniquet to hemostatic or pressure dressing

The 2013 TCCC guidelines stated that after tourniquet placement, reassessment is recommended during the TFC and TACEVAC phases of care and that conversion to hemorrhage control with a hemostatic or pressure dressing should be attempted if evacuation is anticipated to be longer than two hours.³⁵

The Ranger Medic Handbook (4th edition) has a tourniquet conversion procedure that lists four indications for conversion: bleeding is controlled, hemostatic dressing is effective, evacuation is prolonged (in time or distance), or the user is relocating the tourniquet distally. If any indication is present, then the tourniquet is loosened and the wound assessed for bleeding.³⁷

Additional published guidelines for tourniquet conversion include the report of a 2003 Army expert panel that recommend tourniquet conversion to hemostatic or pressure dressing if the casualty is not in shock and conversion can be monitored regularly for rebleeding; the panel recommended not to loosen the tourniquet if there is an amputation or arterial injury or if the tourniquet has been in place ≥ 6 hrs.³⁸

Doyle et al published a similar tourniquet removal algorithm intended for civilian EMS: in the absence of circulatory shock, unstable clinical situation, or limited personnel/resources preventing placement of a pressure dressing or monitoring for rebleeding, tourniquets may be considered for removal. For an amputated extremity, leave the tourniquet on. Otherwise, apply a pressure dressing and loosen the tourniquet. If significant rebleeding occurs, retighten the tourniquet until arrival at higher level of care.³⁶

Periodic loosening of tourniquets for the purpose of reperfusing the limb has resulted in incremental exsanguination and has no role on the battlefield, as described by Wolff and Adkins in 1945 and re-emphasized by Walters and Mabry in 2005.^{24,38} Additionally, periodic reperfusion of the ischemic limb may increase the amount of damage to the limb by worsening of the ischemia-reperfusion injury.³⁹

Three criteria for tourniquet conversion to a hemostatic or pressure dressing were selected for inclusion in this 2014 update to the TCCC guidelines: the casualty is not in shock, it is possible to monitor the wound closely for bleeding, and the tourniquet is not being used to control bleeding from an amputated extremity. All three criteria must be met before considering tourniquet conversion.

Complications of tourniquet use

A thorough understanding of the risks of tourniquet use has led to process improvements that have allowed for an improved risk-to-benefit ratio for tourniquet use during the 21st century wars.

Potential complications of tourniquet use are many, and have been reported in great detail in the orthopedic surgery literature.^{40,41} However, the complications from emergency tourniquet use are much more difficult to quantify in comparison to elective surgery due to the effects of the injury itself which may contribute to similar outcomes. Kragh et al selected the following complications to report in their prospective observational study of tourniquet use: amputation, fasciotomy, clot, palsy, myonecrosis, acute renal failure, significant pain, and rigor.^{1,19} In general, complications of tourniquet use result from direct pressure at the site of the tourniquet, venous congestion, rebleeding from a partially occlusive tourniquet, or ischemia induced by arterial occlusion.

Direct pressure injuries are risked with narrower tourniquets and higher tourniquet pressures, resulting in nerve palsy, vascular injury, or direct tissue injury. Such iatrogenic injuries may be minimized through the use of wider tourniquets at lower compression pressures.^{42,43} Device selection has been instrumental in reducing direct pressure injuries. TCCC guidelines and training have also recommended placement of a second tourniquet side-by-side with the first if the initial application is ineffective, thereby effectively widening the tourniquet, an innovation from users in the field that led Dr. John Kragh to clarify its usefulness and to propose its implementation formally.³⁵ Conversion to wider pneumatic tourniquets, as is frequently done on arrival to a surgical facility, may further reduce the risk of pressure injuries.

The “venous tourniquet” occurs when the tourniquet is tight enough to occlude venous outflow from the limb while failing to occlude arterial inflow. Continued inflow of blood with impaired outflow leads to loss of blood in the body’s core and swelling of the distal limb with higher risk of compartment syndrome, but may also increase the amount of wound bleeding, particularly from venous injuries. Kragh et al in 2008 reported that 44 of 232 casualties with prehospital applied tourniquets had persistent bleeding on arrival to a combat support hospital and 43 of the 232 had persistent distal pulses; these casualties experienced an increased morbidity and mortality rate. The authors described the clinical progression associated with ineffective tourniquets: persistent pulse, venous congestion, venous distension, rebleeding after a period of hemorrhage control, expanding hematomas, compartment syndrome, fasciotomy, and death.^{1,19} These observations resulted in two refinements of the TCCC Guidelines in 2008: 1) the elimination of the distal pulse on the extremity was added as a goal of tourniquet application; and 2) the recommendation to use a second tourniquet rather than overtightening the first tourniquet to achieve both bleeding control and stoppage of the distal pulse.³⁵

Clinical evidence indicates that field tourniquet placement may be effective but at the hospital or after resuscitation is begun, the tourniquet may become ineffective due to an increase in the blood pressure;³² this loss of effectiveness during resuscitation underscores the need for reassessment of tourniquet use so that the tourniquet may be retightened or adjusted. New evidence also indicates that initial tourniquet placement may be effective but within a minute, muscle tension under the tourniquet may lessen causing the tourniquet to become ineffective;⁴⁴ this early loss of effectiveness underscores the need for early reassessment of tourniquet use so that the tourniquet may be retightened or adjusted.

Training must emphasize that tourniquets need to achieve both cessation of bleeding and stoppage of the distal pulse and that frequent reassessment is essential to maintain effectiveness of the tourniquet. It is recognized that partial amputation and isolated arterial injury may result in no palpable distal pulse, while in many combat situations obtaining full exposure and removing footwear to check pulses may be delayed; in such cases, visibly confirming control of wound hemorrhage suffices. In darkness, palpation for pulses may be more useful than observing for hemorrhage.

Ischemic complications increase as tourniquet time increases. There is no consensus on an absolutely safe duration for tourniquet use, however a range of 1-3 hours has been suggested, with 2 hours accepted as a useful guideline for safe usage during elective surgery.^{1,45-49} Serum creatine phosphokinase (CPK) has been used as a marker for limb muscle damage at and distal to the tourniquet. In dogs, the CPK does not increase after one hour of ischemia, but rises after 2-3 hours of ischemia.⁵⁰ In addition, Olivecrona et al demonstrated that tourniquet times longer than 100 minutes were associated with an increase in complications after knee arthroplasty (independent of comorbidities or primary/revision indication) with the odds of a complication

increasing by 20% for each 10 minutes of longer tourniquet time throughout a range of 39-156 minutes.⁵¹ Other authors have postulated that the effects of traumatic injury and blood loss may reduce the ischemic tolerance of the limb in comparison to elective surgery, suggesting that safe tourniquet times may be shorter than expected for patients in shock.^{52,53}

In general, minimizing tourniquet time is the most effective strategy to minimize the risks of tourniquet-related injury. Minimizing harm is particularly important for those casualties who may have had a tourniquet placed for hemorrhage that is not life-threatening, which may frequently occur during real-world scenarios during CUF. While 2 hours is generally considered a safe duration of tourniquet use, the CoTCCC supports conversion of the tourniquet to a hemostatic or pressure dressing at the earliest opportunity rather than routinely waiting 2 hours; this 2014 revision to the TCCC guidelines strengthens and clarifies the recommendation to convert tourniquets as soon as possible during the TFC or TACEVAC phases of care.

The CoTCCC has also considered the question of whether to remove a tourniquet that has been used for prolonged periods during TFC or TACEVAC care. It should be emphasized that if tourniquet conversion has been attempted unsuccessfully within 2 hours of initial use, then repeated attempts at tourniquet conversion are not recommended. In some cases, a second attempt to convert the tourniquet may be indicated, particularly if conditions for wound management have significantly improved, however, in general, the need to attempt tourniquet conversion after 2 hours should only arise when earlier conversion was neglected or impractical due to circumstances.

Prolonged ischemia can result in irreversible damage to limbs necessitating amputation. Skeletal muscle ischemia-reperfusion injury results in accumulation of lactic acid and breakdown of cells with release of myoglobin, potassium, and other intracellular products into

circulation.^{54,55} Release of tourniquets also causes transient hypotension, attributed to vasodilation of the reperfused limb and blood loss.^{47,56} Myoglobinemia may result in varying degrees of kidney damage beginning at the time of limb reperfusion, with gradual progression of hyperkalemia and acidosis which may need to be treated with renal replacement therapy.⁵⁴

The time length between ischemia-reperfusion and life-threatening hypotension or renal failure depends in part on the volume of ischemic tissue as well as the temperature of the limb. A published consensus opinion held that removal of a tourniquet that has been in place longer than 6 hours without successful conversion should not be removed until the casualty has reached a surgical facility.³⁸

Research in animals dating back to the 1910s shows that irreversible ischemic damage to muscle occurs when arterial inflow is occluded for longer than 5-6 hours at room temperature,⁵⁷⁻⁵⁹ however the threshold for meaningful functional recovery may actually be shorter.⁵² The effects of traumatic injury and blood loss on ischemic time have been shown to reduce the threshold to less than 3 hours for functional recovery in an animal model.⁵³ On the contrary, the effect of local hypothermia has been shown to have a protective effect on muscles exposed to tourniquet-induced ischemia.⁶⁰⁻⁶²

The length of safe use of emergency limb tourniquets is complicated by the observation that many tourniquets may not completely occlude arterial inflow and limb cooling may limit damage to ischemic tissue, therefore actual cases do not replicate laboratory conditions. Functional recovery after prolonged use has also been reported.^{49,63} Therefore, there is no absolute time at which amputation of an ischemic limb is inevitable, however, as a general rule, the risks of muscle death, rhabdomyolysis, compartment syndrome, and limb loss increase after 3-4 hours of ischemia, and there is a high rate of irreversible limb damage after 6 hours. Due to

the risks of rhabdomyolysis, shock, and renal failure with progressive hyperkalemia and acidosis, we suggest that tourniquets that have been in place for longer than 6 hours should not be removed outside of a closely monitored setting, preferably with laboratory capability.

Future reductions in tourniquet-related complications may be achievable through improved training that minimizes use of non-indicated tourniquets, that recognizes and corrects ineffective tourniquets, and that minimizes the duration of ischemia through early conversion of tourniquets to hemostatic or pressure dressings in the TFC or TACEVAC phases of care. In addition, an ongoing commitment to refining tourniquet designs may further minimize tissue damage and more reliably occlude arterial inflow.

“High and tight” placement

The issue of whether to place a tourniquet as proximal as possible on a limb versus clearly proximal to the identified bleeding site during the CUF phase of TCCC has not been specifically addressed in the published literature, although it has been discussed in many forums. Tourniquet placement distal to an unseen wound may be fatal. Kragh et al described 4 of 428 patients with tourniquets placed distal to the most proximal wound, and two of these four patients died.¹

Arguments in favor of “high and tight” placement are that it is not advisable to fully expose a wound during CUF and that placement of the tourniquet as proximal as possible on the injured limb is the safest method to avoid placement distal to an unseen wound. On the contrary, upper arm and thigh placement tends to be less effective than more distal placement because of the greater girth compressed compared to the forearm and calf¹ and proximal tourniquet placement leads to a greater volume of ischemic tissue. Some wounds may be clearly seen as only distal (without any proximal wound) which may allow more distal tourniquet use with a

lesser pathophysiologic burden.

As reported in the 2012 Joint Theater Trauma System review of prehospital trauma care in Combined Joint Operating Area-Afghanistan: “This application technique (“high and tight”) combined with prolonged tourniquet time has been associated with complications in at least two non-US casualties...If a “high and tight” tourniquet is placed during care under fire, emphasize reassessment and repositioning at the earliest opportunity during Tactical Field Care.”⁶⁴

Discussion at the August 2014 meeting of the CoTCCC recommended placement of tourniquets as proximal on the limb as possible during the CUF phase, recognizing that a strong emphasis should be placed on reassessing the tourniquet during both the TFC and TACEVAC phases of care. It was also conceded that if the bleeding site is readily apparent, particularly for non-blast injuries, then placement just proximal to the bleeding site was acceptable. It was noted that any mechanism that creates multiple open wounds, such as blast, makes assessment of the injured limb more challenging and increases the risk of missing a wound exsanguination if the tourniquet is not placed as proximally as possible on the limb during the CUF phase of TCCC.

Any “high and tight” tourniquet should at the first opportunity be moved to a position directly on the skin 2-3 inches above the wound or converted to a hemostatic or pressure dressing at the first opportunity. The recommended method for repositioning the tourniquet is to remove the clothing and place a second tourniquet just above the wound, then loosen the “high and tight” original tourniquet. If bleeding is not controlled during the assessment of wound hemorrhage, then the loosened proximal tourniquet should be moved distal to become side-by-side with the second tourniquet; the tourniquets are tightened until bleeding is stopped and the distal pulse is not palpable.

Single slit routing

The CAT is currently the most commonly fielded tourniquet in the U.S. military and is one of two tourniquets (along with the SOFTT) recommended by the CoTCCC for use on the battlefield. A 2013 survey of recovered tourniquets showed that 75% of tourniquets were CATs and 20% were SOFTTs.⁶⁵

The manufacturer's instructions for use (IFU) of the CAT recommend single slit routing of the band through the buckle only for one-handed application to the upper extremity; double slit routing is recommended for all lower extremity applications. One-handed application to the lower extremity is not addressed in the IFU, however, and may be an additional indication for single slit routing.⁶

Analysis of recovered tourniquets by the Armed Forces Medical Examiner in 2012 demonstrated that the standard-issue CAT was commonly placed with the band routed once through the buckle ("single slit routing") in 35% of lower extremity placements and 53% of upper extremity placements.⁴ Similar findings were confirmed by Kragh et al in a 2013 analysis of recovered tourniquets, showing that 37% of CATs were routed once through the buckle; the samples of these two studies overlapped substantially but not completely.⁶⁵

CAT effectiveness for single or double slit routing has not been assessed in a clinical series, however the question has been addressed in a laboratory study. In a manikin model, the effectiveness for hemorrhage control was equal for both routings, while time to stop bleeding and total blood loss volumes were significantly less with single slit routing.⁶

Discussion at the August 2014 meeting of the CoTCCC led to the recommendation for single slit routing of the CAT during Care Under Fire. It was noted that the 6th generation CAT has an increased length of 37.5 inches, compared to 31 inches for earlier versions, which further increases the contact area of Omni-Tape® Velcro for larger thighs. This increased contact area

helped to alleviate concerns regarding anecdotal experience with earlier versions slipping in some cases. Buckle breakage, another hypothetical concern with single slit routing, has never been reported for the CAT. It was also noted that the critical first step in effective tourniquet placement is to ensure that the band is as tight as possible on the limb prior to turning the windlass; single slit routing of the band facilitates such tightening while double slit routing may impair the initial tightening of the band since the Velcro may adhere to itself during application and tension is partially lost while routing through the second slit, particularly with inexperienced users.

Training issues in tourniquet use

Tourniquet use for minimal injuries or bleeding that is not life-threatening has no benefit. If placed during the CUF phase, such a tourniquet should be converted to a hemostatic or pressure dressing at the first opportunity.

The recommended technique for converting a tourniquet to a hemostatic or pressure dressing is to first place the dressing then loosen the tourniquet while observing closely for bleeding through the dressing. The loosened tourniquet should be left in place 2-3 inches above the wound in case re-bleeding occurs.

Conversion of a tourniquet to a hemostatic or pressure dressing should be attempted at the first opportunity, not more than 2 hours after initial application. If the initial conversion attempt is unsuccessful due to re-bleeding, repeated attempts to convert the tourniquet should not be performed due to the risk of incremental exsanguination. In some cases, a second attempt to convert the tourniquet may be indicated, particularly if conditions for wound management have significantly improved due to better lighting, supplies, manpower, etc.

Tourniquets applied in situations where assessment is very limited such as CUF, mass casualty events, or multiple life-threatening injuries in the same casualty, should be applied “high and tight” (as proximal as possible) on the injured limb to avoid inadvertent placement distal to an unseen injury.

To minimize the damage that may be induced by the tourniquet, care providers are instructed to follow certain “rules of thumb” when applying or repositioning tourniquets during TFC or TACEVAC care: place the tourniquet as distally as possible, but at least 5 cm proximal to the injury; avoid joints; apply the tourniquet over exposed skin to avoid slipping; and convert to hemostatic or pressure dressing whenever possible.³¹

Up to 24% of limbs have 2 tourniquets placed. King et al described one casualty with three tourniquets placed far apart from one another making them act independently as single, independent, and narrow devices rather than together side-by-side as if one wide device.³

When ongoing limb bleeding or distal pulses were detected (generally after exposing the wound), the medics tightened tourniquets under supervision of the surgeon until distal pulses became absent. All medics were surprised as to how tight a tourniquet must be to stop arterial flow; that is, to change a venous tourniquet into an arterial tourniquet.³

TCCC courses must reinforce the distinction between venous and arterial tourniquets in patients without amputations. Venous tourniquets do not occlude arterial inflow to an injured limb but promote venous congestion. Venous tourniquets soon increase bleeding from injured limbs and must be avoided.^{19,66}

An increase in blood pressure during resuscitation may result in rebleeding or return of the distal pulse.²⁰ Medics should also be aware that initial tourniquet placement may be effective

but within a minute, muscle tension under the tourniquet may lessen causing the tourniquet to become ineffective.⁴⁴ Ongoing reassessment of tourniquets is necessary.

TCCC courses must also reinforce the need to attempt conversion of tourniquets to hemostatic or pressure dressings as soon as possible, considering the tactical and clinical situation. All wounds must be monitored closely for rebleeding. Major traumatic amputations require continued use of a tourniquet until arrival to surgery, and conversion to a hemostatic or pressure dressing should not be attempted.

Cooling ischemic muscle reduces damage to the muscle.⁶⁰⁻⁶² Even 2-3°C reduction in skeletal muscle temperature may reduce muscle necrosis after extended tourniquet application.⁶⁷ Cold environmental temperatures were credited for successful limb salvages after tourniquet applications up to 8 hours in World War II.²⁴ Exposure of the limb to take advantage of cool environmental temperatures was also recommended by an expert panel convened in 2003.³⁸ Packing of an injured limb with snow or ice, however, is not recommended due to the risk of further tissue injury.⁴⁹

As demonstrated by the Ranger model, medical training must also be incorporated into each unit's combat training exercises and real-world training scenarios, rather than just being rehearsed independently under static conditions.^{34,64}

Teach tourniquet application during field training and Care Under Fire exercises. Classroom training alone is not adequate.

An algorithm for tourniquet placement during CUF and reassessment during TFC and TACEVAC care is illustrated in Figure 1.

Conclusions

1. A decrease in the frequency of preventable deaths has been achieved through widespread training, dissemination and use of tourniquets. The likelihood of tourniquet morbidity had been reduced through selection of better devices, more training of potential users, and more rapid evacuation. In order to minimize complications, it is important that training emphasizes early conversion of no longer needed tourniquets and reassessment of tourniquet placement to ensure that hemorrhage is stopped and a venous tourniquet is avoided, particularly when evacuation time is long.
2. No longer needed tourniquets should be converted to hemostatic or pressure dressings as soon as possible if the criteria for safe removal are met in order to reduce tourniquet pain and minimize the risks complications. If the tourniquet is still on the extremity two hours after placement, a mandatory re-assessment of the continued need for the tourniquet should occur.
3. The goals of tourniquet placement are to control hemorrhage and to stop the distal pulse. Tactical and clinical situations dictate which goal(s) can be monitored, however the likelihood of maximum benefit and minimum risk occurs only when both goals are attained.
4. Tourniquets placed during Care Under Fire should be positioned clearly proximal to the bleeding site(s). If the site of life-threatening bleeding is not readily apparent, the tourniquet should be placed “high and tight” (as proximal as possible) on the injured extremity as soon as possible.
5. Single slit routing of the CAT band through the buckle is effective and may reduce blood loss and time for application, and is therefore recommended during the CUF phase. Store

the CAT single routed, the ready-to-go configuration, to save time whenever use is needed; double-routed stowage wastes time during initial application.

Proposed Change

Current Wording in the TCCC Guidelines:

Care Under Fire

7. Stop *life-threatening* external hemorrhage if tactically feasible:

- Direct casualty to control hemorrhage by self-aid if able.
- Use a CoTCCC-recommended tourniquet for hemorrhage that is anatomically amenable to tourniquet application.
- Apply the tourniquet proximal to the bleeding site, over the uniform, tighten, and move the casualty to cover.

Tactical Field Care

4. Bleeding

a. Assess for unrecognized hemorrhage and control all sources of bleeding. If not already done, use a CoTCCC-recommended tourniquet to control life-threatening external hemorrhage that is anatomically amenable to tourniquet application or for any traumatic amputation. Apply directly to the skin 2-3 inches above wound.

b. For compressible hemorrhage not amenable to tourniquet use or as an adjunct to tourniquet removal (if evacuation time is anticipated to be longer than two hours), use Combat Gauze as the CoTCCC hemostatic dressing of choice. Celox Gauze and ChitoGauze may also be used if Combat Gauze is not available. Hemostatic dressings should be applied with at least 3 minutes of direct pressure.

Before releasing any tourniquet on a casualty who has been resuscitated for hemorrhagic shock, ensure a positive response to resuscitation efforts (i.e., a peripheral pulse normal in character and normal mentation if there is no traumatic brain injury (TBI). If the bleeding site is appropriate for use of a junctional tourniquet, immediately apply a CoTCCC-recommended junctional tourniquet. Do not delay in the application of the junctional tourniquet once it is ready for use. Apply hemostatic dressings with direct pressure if a junctional tourniquet is not available or while the junctional tourniquet is being readied for use.

c. Reassess prior tourniquet application. Expose wound and determine if tourniquet is needed. If so, move tourniquet from over uniform and apply directly to skin 2-3 inches above wound. If a tourniquet is not needed, use other techniques to control bleeding.

d. When time and the tactical situation permit, a distal pulse check should be accomplished. If a distal pulse is still present, consider additional tightening of the tourniquet or the use of a second tourniquet, side by side and proximal to the first, to eliminate the distal pulse.

e. Expose and clearly mark all tourniquet sites with the time of tourniquet application. Use an indelible marker.

Tactical Evacuation Care

3. Bleeding

a. Assess for unrecognized hemorrhage and control all sources of bleeding. If not already done, use a CoTCCC-recommended tourniquet to control life-threatening external hemorrhage that is anatomically amenable to tourniquet application or for any traumatic amputation. Apply directly to the skin 2-3 inches above wound.

b. For compressible hemorrhage not amenable to tourniquet use or as an adjunct to tourniquet removal (if evacuation time is anticipated to be longer than two hours), use Combat Gauze as the

CoTCCC hemostatic dressing of choice. Celox Gauze and ChitoGauze may also be used if Combat Gauze is not available. Hemostatic dressings should be applied with at least 3 minutes of direct pressure.

Before releasing any tourniquet on a casualty who has been resuscitated for hemorrhagic shock, ensure a positive response to resuscitation efforts (i.e., a peripheral pulse normal in character and normal mentation if there is no TBI.) If the bleeding site is appropriate for use of a junctional tourniquet, immediately apply a CoTCCC recommended junctional tourniquet. Do not delay in the application of the junctional tourniquet once it is ready for use. Apply hemostatic dressings with direct pressure if a junctional tourniquet is not available or while the junctional tourniquet is being readied for use.

c. Reassess prior tourniquet application. Expose wound and determine if tourniquet is needed. If so, move tourniquet from over uniform and apply directly to skin 2-3 inches above wound. If a tourniquet is not needed, use other techniques to control bleeding.

d. When time and the tactical situation permit, a distal pulse check should be accomplished. If a distal pulse is still present, consider additional tightening of the tourniquet or the use of a second tourniquet, side by side and proximal to the first, to eliminate the distal pulse.

e. Expose and clearly mark all tourniquet sites with the time of tourniquet application. Use an indelible marker.

Proposed new Wording in the TCCC Guidelines:

Care Under Fire

7. Stop life-threatening external hemorrhage if tactically feasible:

- Direct casualty to control hemorrhage by self-aid if able.
- Use a CoTCCC-recommended **limb** tourniquet for hemorrhage that is anatomically

amenable to tourniquet **use**.

- Apply the **limb** tourniquet over the uniform **clearly proximal to the bleeding site(s)**.

If the site of the life-threatening bleeding is not readily apparent, place the tourniquet “high and tight” (as proximal as possible) on the injured limb and move the casualty to cover.

Tactical Field care

4. Bleeding

a. Assess for unrecognized hemorrhage and control all sources of bleeding. If not already done, use a CoTCCC-recommended **limb** tourniquet to control life-threatening external hemorrhage that is anatomically amenable to tourniquet **use** or for any traumatic amputation. Apply directly to the skin 2-3 inches above the wound. **If bleeding is not controlled with the first tourniquet, apply a second tourniquet side-by-side with the first.**

b. For compressible hemorrhage not amenable to **limb** tourniquet use or as an adjunct to tourniquet removal, use Combat Gauze as the CoTCCC hemostatic dressing of choice. Celox Gauze and ChitoGauze may also be used if Combat Gauze is not available. Hemostatic dressings should be applied with at least 3 minutes of direct pressure. If the bleeding site is **amenable to** use of a junctional tourniquet, immediately apply a CoTCCC-recommended junctional tourniquet. Do not delay in the application of the junctional tourniquet once it is ready for use. Apply hemostatic dressings with direct pressure if a junctional tourniquet is not available or while the junctional tourniquet is being readied for use.

c. Reassess prior tourniquet application. Expose the wound and determine if a tourniquet is needed. If it is, replace any **limb** tourniquet placed over the uniform with **one** applied directly to the skin 2-3 inches above wound. **Ensure that bleeding is stopped. When possible,** a distal

pulse should be **checked**. If **bleeding persists or** a distal pulse is still present, consider additional tightening of the tourniquet or the use of a second tourniquet side-by-side with the first to eliminate **both bleeding and** the distal pulse.

d. **Limb tourniquets and junctional tourniquets should be converted to hemostatic or pressure dressings as soon as possible if three criteria are met: the casualty is not in shock; it is possible to monitor the wound closely for bleeding; and the tourniquet is not being used to control bleeding from an amputated extremity. Every effort should be made to convert tourniquets in less than 2 hours if bleeding can be controlled with other means. Do not remove a tourniquet that has been in place more than 6 hours unless close monitoring and lab capability are available.**

e. Expose and clearly mark all tourniquet sites with the time of tourniquet application.

Use an indelible marker.

Tactical Evacuation Care

3. Bleeding

a. Assess for unrecognized hemorrhage and control all sources of bleeding. If not already done, use a CoTCCC-recommended **limb** tourniquet to control life-threatening external hemorrhage that is anatomically amenable to tourniquet **use** or for any traumatic amputation. Apply directly to the skin 2-3 inches above the wound. **If bleeding is not controlled with the first tourniquet, apply a second tourniquet side-by-side with the first.**

b. For compressible hemorrhage not amenable to **limb** tourniquet use or as an adjunct to tourniquet removal, use Combat Gauze as the CoTCCC hemostatic dressing of choice. Celox Gauze and ChitoGauze may also be used if Combat Gauze is not available. Hemostatic dressings should be applied with at least 3 minutes of direct pressure. If the bleeding site is **amenable to**

use of a junctional tourniquet, immediately apply a CoTCCC-recommended junctional tourniquet. Do not delay in the application of the junctional tourniquet once it is ready for use. Apply hemostatic dressings with direct pressure if a junctional tourniquet is not available or while the junctional tourniquet is being readied for use.

c. Reassess prior tourniquet application. Expose the wound and determine if a tourniquet is needed. If it is, replace any **limb** tourniquet placed over the uniform with **one** applied directly to the skin 2-3 inches above wound. **Ensure that bleeding is stopped. When possible**, a distal pulse should be **checked**. If **bleeding persists or** a distal pulse is still present, consider additional tightening of the tourniquet or the use of a second tourniquet side-by-side with the first to eliminate **both bleeding and** the distal pulse.

d. **Limb tourniquets and junctional tourniquets should be converted to hemostatic or pressure dressings as soon as possible if three criteria are met: the casualty is not in shock; it is possible to monitor the wound closely for bleeding; and the tourniquet is not being used to control bleeding from an amputated extremity. Every effort should be made to convert tourniquets in less than 2 hours if bleeding can be controlled with other means. Do not remove a tourniquet that has been in place more than 6 hours unless close monitoring and lab capability are available.**

e. Expose and clearly mark all tourniquet sites with the time of tourniquet application. Use an indelible marker.

Considerations for Future Research and Development

Enforce collection of and capitalize on data from prehospital casualty cards, prehospital after action reports, and prehospital trauma registries to further tourniquet study analysis and performance improvement.

Develop improved tourniquet management strategies for prolonged field care scenarios, such as methods for cooling the extremity or adjuncts to removing tourniquets that have been in placed for lengthy periods.

Conduct more research to improve tourniquet designs, best practices, and alternative interventions.

Conduct detailed outcome analyses of limb morbidity and tourniquet use, including use durations, functional outcomes, infection rates, and timing of limb losses.

Conduct studies to measure rates of hypotension, arrhythmia, cardiac arrest, rhabdomyolysis and progressive acidosis resulting from tourniquet release in order to improve clinical recommendations as to how to release a tourniquet or manage revascularization after 6 hours of ischemia.

Develop cost effective, self-monitoring, intelligent tourniquets that detect arterial flow and accurately record duration of use.

Acknowledgments

The authors gratefully acknowledge the research assistance provided by Mrs. Danielle Davis of the Joint Trauma System. The authors also thank the Department of Defense Trauma Registry for providing much of the casualty data discussed in this paper.

Disclaimers

The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the Department of the Army or the Department of Defense. This recommendation is intended to be a guideline only and is not a substitute for clinical judgment.

References

1. Kragh JF Jr, Walters TJ, Baer DG, Fox CJ, Wade CE, Salinas J, Holcomb JB. Practical use of emergency tourniquets to stop bleeding in major limb trauma. *J Trauma*. 2008;64:S38-S50.
2. Kragh JF Jr, Wade CE, Baer DG, Jones JA, Walters TJ, Hsu JR, Wenke JC, Blackbourne LH, Holcomb JB. Fasciotomy rates in Operations Enduring Freedom and Iraqi Freedom: association with injury severity and tourniquet use. *J Orthop Trauma*. 2011;25:134-139.
3. King DR, van der Wilden G, Kragh JF Jr, Blackbourne LH. Forward assessment of 79 prehospital battlefield tourniquets used in the current war. *J Spec Oper Med*. 2012 Winter;12:33-38.
4. *Naval Operational Medical Lessons Learned, Feedback to the Field #11: Application of the Combat Action Tourniquet*. Feb 2012. Available at <https://www.dmsb.mil/jmteLinksResources.asp>; accessed July 5, 2014.
5. Kragh JF Jr, O'Neill ML, Walters TJ, Dubick MA, Baer DG, Wade CE, Holcomb JB, Blackbourne LH. The military emergency tourniquet program's lessons learned with devices and designs. *Mil Med*. 2011;176:1144-1152.
6. Clumpner BR, Polston RW, Kragh JF Jr, Westmoreland T, Harcke HT, Jones JA, Dubick MA, Baer DG, Blackbourne LH. Single versus double routing of the band in the Combat Application Tourniquet. *J Spec Oper Med*. 2013 Spring;13:34-41.
7. Blackbourne LH, Baer DG, Eastridge BJ, Kheirabadi B, Bagley S, Kragh JF Jr, Cap AP, Dubick MA, Morrison JJ, Midwinter MJ, Butler FK, Kotwal RS, Holcomb JB. Military

medical revolution: Prehospital combat casualty care. *J Trauma Acute Care Surg.* 2012;73:S372-S377.

8. Kragh JF Jr, Swan KG, Smith DC, Mabry RL, Blackbourne LH. Historical review of emergency tourniquet use to stop bleeding. *Am J Surg.* 2012;203:242-252.
9. Kragh JF Jr, Walters TJ, Baer DG, Fox CJ, Wade CE, Salinas J, Holcomb JB. Survival with emergency tourniquet use to stop bleeding in major limb trauma. *Ann Surg.* 2009;249:1-7.
10. Kragh JF Jr, Littrel ML, Jones JA, Walters TJ, Baer DG, Wade CE, Holcomb JB. Battle casualty survival with emergency tourniquet use to stop limb bleeding. *J Emerg Med.* 2011;41:590-597.
11. Butler FK Jr, Hagmann J, Butler EG. Tactical combat casualty care in special operations. *Mil Med.* 1996;161:S3-S16.
12. *Emergency War Surgery*, First United States Revision. U.S. Government Printing Office: Washington, D.C.; 1975.
13. *Emergency War Surgery*, Second United States Revision. U.S. Government Printing Office: Washington, D.C.; 1988.
14. Walters TJ, Wenke JC, Kauvar DS, McManus JG, Holcomb JB, Baer DG. Effectiveness of self-applied tourniquets in human volunteers. *Prehosp Emerg Care.* 2005;9:416-422.
15. Holcomb JB, McMullin NR, Pearse L, Caruso J, Wade CE, Oetjen-Gerdes L, Champion HR, Lawnick M, Farr W, Rodriguez S, Butler FK. Causes of death in U.S. special operations forces in the Global War on Terrorism. *Ann Surg.* 2007;245:986-991.
16. Kragh JF Jr, Walters TJ, Westmoreland T, Miller RM, Mabry RL, Kotwal RS, Ritter BA, Hodge DC, Greydanus DJ, Cain JS, Parsons DL, Edgar EP, Harcke HT, Baer DG,

- Dubick MA, Blackbourne LH, Montgomery HR, Holcomb JB, Butler FK. Tragedy into Drama: an American history of tourniquet use in the current war. *J Spec Oper Med*. 2013 Fall;13:5-25.
17. Butler FK Jr, Blackbourne LH. Battlefield trauma care then and now: a decade of Tactical Combat Casualty Care. *J Trauma Acute Care Surg*. 2012;73:S395-S402.
18. Ritenour AE, Dorlac WC, Rang R, Woods T, Jenkins DH, Flaherty SF, Wade CE, Holcomb JB. Complications after fasciotomy revision and delayed compartment release in combat patients. *J Trauma*. 2008;64:S153-S161.
19. Kragh JF Jr, O'Neill ML, Walters TJ, Jones JA, Baer DG, Gershman LK, Wade CE, Holcomb JB. Minor morbidity with emergency tourniquet use to stop bleeding in severe limb trauma: research, history, and reconciling advocates and abolitionists. *Mil Med*. 2011;176:817-823.
20. Kragh JF Jr, Beebe EF, O'Neill ML, Beekley AC, Dubick MA, Baer DG, Blackbourne LH. Performance improvement in emergency tourniquet use during the Baghdad surge. *Am J Emerg Med*. 2013;31:873-875.
21. Welling DR, Burris DG, Hutton JE, Minken SL, Rich NM. A balanced approach to tourniquet use: lessons learned and relearned. *J Am Col Surg*. 2006;203:106-115.
22. Gross SD. *A Manual of Military Surgery, or, Hints on the Emergencies of Field, Camp and Hospital Practice*. J.B. Lippincott: Philadelphia, 1862.
23. *Injuries and diseases of war* (reprint of the official British manual). Washington, DC; 1918.
24. Wolff LH, Adkins TF. Tourniquet problems in war injuries. *Bulletin of the U. S. Army Medical Department*. 1945;37:77-84.

25. Bellamy RF. Combat trauma overview. In: Zajtcuk R, Grande CM, eds. Textbook of Military Medicine, Anesthesia and Perioperative Care of the Combat Casualty. Falls Church, VA: Office of the Surgeon General, United States Army; 1995:1–42.
26. Bellamy RF: The causes of death in conventional land warfare: implications for combat casualty care research. *Mil Med.* 1984;149:55-62.
27. Calkins MD, Snow C, Costello M, Bentley TB. Evaluation of possible battlefield tourniquet systems for the far-forward setting. *Mil Med.* 2000;165:379-384.
28. Butler FK, Holcomb JB, Giebner SG, McSwain NE, Bagian J. Tactical Combat Casualty Care 2007: Evolving Concepts and Battlefield Experience. *Mil Med.* 2007; 172:S1-S19.
29. Kelly JF, Ritenour AE, McLaughlin DF, Bagg KA, Apodaca AN, Mallak CT, Pearse L, Lawnick MM, Champion HR, Wade CE, Holcomb JB. Injury severity and causes of death from Operation Iraqi Freedom and Operation Enduring Freedom: 2003-2004 versus 2006. *J Trauma.* 2008;64:S21-S27.
30. Eastridge B, Mabry R, Seguin 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-S437.
31. Lakstein D, Blumenfeld A, Sokolov T, Lin G, Bssorai R, Lynn M, Ben-Abraham R. Tourniquets for hemorrhage control on the battlefield: A 4-year accumulated experience. *J Trauma.* 2003;54:S221-S225.
32. Beekley AC, Sebesta JA, Blackburne LH, Herbert GS, Kauvar DS, Baer DG, Walters TJ, Mullenix PS, Holcomb JB, 31st Combat Support Hospital Research Group. Prehospital tourniquet use in Operation Iraqi Freedom: effect on hemorrhage control and outcomes. *J Trauma.* 2008;64:S28-37.

33. Kragh JF Jr, O'Neill ML, Beebe DF, Fox CJ, Beekley AC, Cain JS, Parsons DL, Mabry RL, Blackburne L. Survey of the indications for use of emergency tourniquets. *J Spec Oper Med*. 2011 Winter;11:30-38.
34. Kotwal RS, Montgomery HR, Kotwal BM, Champion HR, Butler FK, Mabry RL, Cain JS, Blackburne LH, Mechler KK, Holcomb JB. Eliminating Preventable Death on the Battlefield. *Arch Surg*. 2011;146:1350-1358.
35. Butler FK, Giebner SD, McSwain N, Salomone J, Pons P, eds. Prehospital Trauma Life Support Manual; Seventh Edition – Military Version. November 2010.
36. Doyle GS, Taillac PP. Tourniquets: A review of current use with proposals for expanded prehospital use. *Prehosp Emerg Care*. 2008;12:241-256.
37. Donovan W, Montgomery HR (editors). Ranger Medic Handbook, 4th Edition. Winter Haven, FL: Pentagon Publishing, 2012.
38. Walters TJ, Mabry RL. Issues related to the use of tourniquets on the battlefield. *Mil Med*. 2005;170:770-775.
39. Klenerman, L. The Tourniquet Manual—Principles and Practice. London, Springer-Verlag; 2003:44-46.
40. Orgui E, Parsons A, White T, Longo G, Khan WS. Tourniquet use in upper limb surgery. *Hand*. 2011;6:165-173.
41. Wakai A, Winter DC, Street JT, Redmond PH. Pneumatic tourniquets in extremity surgery. *J Am Acad Orthop Surg*. 2001;9:345-351.
42. Crenshaw AG, Hargens AR, Gershuni DH, Rydevik B. Wide tourniquet cuffs more effective at lower inflation pressures. *Acta Orthop Scand*. 1988;59:447-451.

43. Graham B, Breault MJ, McEwen JA, McGraw RW. Occlusion of arterial flow in the extremities at subsystolic pressures through the use of wide tourniquet cuffs. *Clin Orthop Relat Res.* 1993;286:267-261.
44. Wall PL, Duevel DC, Hassan MB, Welander JD, Sahr SM, Buising CM. Tourniquets and occlusion: the pressure of design. *Mil Med.* 2013;178:578-587.
45. Klenerman L. Tourniquet time—how long? *Hand.* 1980;12:231-234.
46. Fletcher IR, Healy TEJ. The arterial tourniquet. *Ann R Coll Surg Engl.* 1983;65:409-417.
47. Kam PC, Kavanagh R, Yoong FF. The arterial tourniquet: pathophysiological consequences and anesthetic implications. *Anaesthesia.* 2001;56:534-545.
48. Blaisdell FW. The pathophysiology of skeletal muscle ischemia and the reperfusion syndrome: a review. *Cardiovasc Surg.* 2002;10:620-630.
49. Kragh JF Jr, Baer DG, Walters TJ. Extended (16-Hour) tourniquet application after combat wounds: a case report and review of current literature. *J Orthop Trauma.* 2007;21:274-278.
50. Sapega AA, Heppenstall RB, Chance B, Park YS, Sokolow D: Optimizing tourniquet application and release times in extremity surgery. A biochemical and ultrastructural study. *J Bone Joint Surg Am.* 1985;67: 67:303-314.
51. Olivecrona C, Lapidus LJ, Benson L, Blomfeldt R. Tourniquet time affects postoperative complications after knee arthroplasty. *Int Orthop.* 2013;37:827-832.
52. Gifford SM, Propper BW, Eliason JL. The ischemic threshold of the extremity. *Perspect Vasc Surg Endovasc Ther.* 2011;23:81-87.

53. Hancock HM, Stannard A, Burkhardt GE, Williams K, Dixon P, Cowart J, Spencer J, Rasmussen TE. Hemorrhagic shock worsens neuromuscular recovery in a porcine model of hind limb vascular injury and ischemia/reperfusion. *J Vasc Surg.* 2011;53:1052-1062.
54. Malinoski DJ, Slater MS, Mullins RJ. Crush injury and rhabdomyolysis. *Crit Care Clin.* 2004;20:171-192.
55. Klenerman L, Biswas M, Hulands GH, Rhodes AM. Systemic and local effects of the application of a tourniquet. *J Bone Joint Surg Br.* 1980;63:385-388
56. Townsend HS, Goodman SB, Shurman DJ, Hackel A, Brock-Utne JG. Tourniquet release: systemic and metabolic effects. *Acta Anaesthesiol Scand.* 1996;40:1234-1237.
57. Wiggers CJ. Physiology of Shock. Commonwealth Fund, New York, 1950, pp 95-120.
58. Malan E, Tattoni G. Physio- and anatomo-pathology of acute ischemia of the extremities. *J Cardiovasc Surg.* 1963;4:212-225.
59. Labbe R, Lindsay T, Walker PM. The extent and distribution of skeletal muscle necrosis after graded periods of complete ischemia. *J Vasc Surg.* 1987;6:152-157.
60. Irving GA, Noakes TD. The protective role of local hypothermia in tourniquet-induced ischaemia of muscle. *J Bone Joint Surg Br.* 1985;67:297-301.
61. Swanson AB, Livengood LC, Sattel AB. Local hypothermia to prolong safe tourniquet time. *Clin Orthop Relat Res.* 1991;264:200-208.
62. Stahl D, Souder N, Probe R, Sampson W, Tharakan B, Ward R. The effects of hypothermia and L-arginine on skeletal muscle function in ischemia-reperfusion injury. *J Orthop Trauma.* 2012;26:579-584.
63. Dayan L, Sinmann C, Stahl S, Norman D. Complications associated with prolonged tourniquet application on the battlefield. *Mil Med.* 2008;173:63-66.

64. Kotwal R, Butler F, Edgar E, Shackelford SA, Bennett DR, Bailey JA. *Saving lives on the battlefield: A Joint Trauma System review of pre-hospital trauma care in Combined Joint Operating Area—Afghanistan (CJOA-A)*. Joint Trauma System; U.S. Army Institute of Surgical Research; Joint Base Fort Sam Houston Report; 30 January 2013.
65. Kragh JF Jr, Burrows S, Wasner C, Ritter BA, Mazuchowski EL, Brunstetter T, Johnston KJ, Diaz GY, Hodge D, Harcke HT. Analysis of recovered tourniquets from casualties of Operation Enduring Freedom and Operation New Dawn. *Mil Med*. 2013;178;7:806-810.
66. Tien HC, Jung V, Rizoli SB, Acharya SV, MacDonald JC. An evaluation of Tactical Combat Casualty Care interventions in a combat environment. *J Am Coll Surg*. 2008;207:174-178.
67. Skjeldal S, Groggaard B, Nordsletten L, Reikeras O, Svindland A, Torvik A. Protective effect of low-grade hypothermia in experimental skeletal muscle ischemia. *Eur Surg Res*. 1992;24:197-203.

Col Shackelford, MC, USAF is an attending trauma surgeon at the Air Force Center for Sustainment of Trauma and Readiness Skills at the R. Adams Cowley Shock Trauma Center in Baltimore. She is a previous deployed director of the Joint Theater Trauma System.

CAPT (Ret.) Butler, MC, USN was a Navy SEAL platoon commander before becoming a physician. He is an ophthalmologist and a Navy Undersea Medical Officer with over 20 years experience providing medical support to Special Operations forces. Dr. Butler has served as the Command Surgeon for the U.S. Special Operations Command. He is currently the Chair of the Department of Defense's Committee on TCCC and Director of Prehospital Trauma Care at the Joint Trauma System.

COL (Ret.) Kragh, MC, USA has researched hemorrhage control at the USAISR since 2004. He is an orthopedic surgeon who previously served at 3d Ranger Battalion Surgeon from 1990 to 1993. Dr Kragh now studies tourniquets and golf.

CAPT Stevens, MC, USN is board-certified in anesthesiology, pain medicine and critical care medicine. He is a Staff Anesthesiologist and Intensivist at the CAPT James A Lowell Federal Health Care Center and Professor of Medicine at the Rosalind Franklin University of Medicine

and Sciences, North Chicago, IL. He served as the Force Surgeon, Combined Joint Task Force – Horn of Africa from 2013-2014, and previously served in Iraq and Afghanistan.

LTC Seery, MC, USA is an attending surgeon and director at the US Army Trauma Training Center at the Ryder Trauma Center in Miami, FL. He was previously the commander of the 541st FST (Airborne) Forward Surgical Team at Ft. Bragg, NC.

LTC (Ret.) Parsons, SP, USA, is the Army master instructor for prehospital medical care with an extensive physician assistant and medic experience in Special Forces. He is currently at the Medical Education and Training Campus, Department of Combat Medic Training, at Fort Sam Houston, TX.

MSG Harold “Monty” Montgomery, U.S. Army, is a Ranger Medic. He was previously the Senior Medic for the 75th Ranger Regiment and is now the Senior Enlisted Medical Advisor for the U.S. Special Operations Command. He has 8 combat deployments, one for Operation Desert Storm, one for Operation Uphold Democracy, 3 for Operation Enduring Freedom, and 3 for Operation Iraqi Freedom. He is a previous winner of the CoTCCC Award for Outstanding Contributions to TCCC.

COL (Ret.) Kotwal, MC, USA is a family medicine and aerospace medicine physician. He is a former Command Surgeon for the 75th Ranger Regiment and Deputy Command Surgeon for the U.S. Army Special Operations Command. Until recently, he was the Director of Trauma Care Delivery at the Joint Trauma System.

LTC Mabry, MC, USA enlisted in the US Army in 1984. Before attending medical school he served for eleven years as a US Army Ranger and Special Forces medical sergeant. He is also a paramedic, a diving medical technician, high angle rescue instructor, and flight surgeon. He served as the senior search and rescue medic for Task Force Ranger in Mogadishu, Somalia and as a Special Forces battalion surgeon during Operation Enduring Freedom in Afghanistan. His military awards include the Silver Star, the Bronze Star and the Purple Heart. He is a graduate of the US Army Emergency Medicine residency and EMS fellowship in San Antonio, Texas as well as the Army Command and Staff College. He is currently the Director of the Military Emergency Medical Services Fellowship, the largest EMS fellowship in the nation, and the Director of Trauma Care Delivery at the Department of Defense Trauma Center of Excellence at Fort Sam Houston, TX. He is the author of numerous articles and book chapters related to battlefield medical care.

Col Bailey MC, USAF is a trauma surgeon. He is currently the Emeritus Director of the Joint Trauma System. Col Bailey was previously the Director of the Air Force Center for Sustainment of Trauma and Readiness Skills in St. Louis.