Chapter 14

Tourniquets

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Emergency tourniquet use is the most obvious combat orthopedic advance of the current war, and a definitive academic record of lessons learned in Iraq and Afghanistan is due. Tourniquet treatment practices in combat casualty care are plainly different from routine civilian care, especially regarding the rate of casualties seen with tourniquets.[1,2] Emergency tourniquets are one of the most controversial topics in first aid and orthopedics, and recommendations have changed recently since military services have evidenced major life-saving benefits with minor morbidity if the right devices are used at the right time for the right casualties in the right way.[2-6] However, until recently, most opinions have been that tourniquet use is best avoided or used as a last resort,[7] and so few providers have compiled experience with hundreds of cases except for a few forward military surgeons.

The aim of this chapter is to report the emergency tourniquet lessons learned from a large emergency tourniquet program and, in particular, offer recommendations for clinical use.

Historical Background of Emergency Tourniquet Use

The historical record of tourniquet use has been poorly documented from the Neolithic Era until recently, and much of the controversy was rooted in a paucity of absence of evidence on whether tourniquets should be used emergently. Given so little evidence, any plausible argument could not be refuted. Key historical developments in emergency tourniquet use include the first definite recorded use of a battlefield tourniquet by Étienne J. Morel at the siege of Besançon in 1674, Jean-Louis Petit's demonstration of his screw tourniquet for surgical amputation in Paris in 1718, Joseph Lister's tourniquet use in elective surgery in Britain in 1864, and Lorenz Bohler's detailed lessons learned in Austria in the World Wars.[8,9] Wolf and Adkins in World War II noted 200 cases and generally gave favorable outcomes and offered pearls and pitfalls, but there was little depth to the data reported.[10] Although Wolf and Adkins' report had little data, it was the largest case series reported to that date. Later, the US military analyzed preventable causes of death in the Vietnam War and then again in Somalia, and tourniquets were thought to be the most practical way to prevent the most common cause of preventable battlefield death.[11-16]

In 2003, the Israelis reported their experience; and although their report on 91 cases was smaller than Wolf and Adkins' 200, the data were broader and deeper.[17] The Israeli study showed that all cases survived and had infrequent morbidity. The 2003 Israeli study brought emergency tourniquet knowledge up to the current war, in which the knowledge was to soon pivot.

Situation in 2001 at the Beginning of the Current War

When the current war began in 2001, there was no good tourniquet available for the battlefield. A compelling scientific case was made over time in

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recent wars that battlefield hemorrhage was a leading cause of death, limb exsanguination was plausibly preventable with hemorrhage control devices like tourniquets, and isolated limb exsanguination was the foremost preventable cause of death on the battlefield.[11] Epidemiologically, the frequency of isolated limb exsanguination has appeared to be about 7% in a few wars where it was estimated[11,12,18]; and so in combat, this lethal problem is common. Until recently in war, surgeons rarely offered substantial evidence that emergency hemorrhage control of limb exsanguination improves survival.[6,19] In the mid-1980s, the Israelis issued emergency tourniquets widely to their soldiers and evidenced that there were few adverse events, but they were criticized for their inability to show life-saving benefit.[17,20,21]

Figure 14-1. Combat application tourniquet. Photograph of the standard issue tourniquet for US soldiers deploying to war, the Combat Application Tourniquet (CAT, photograph used by permission of North American Rescue). The CAT is a strap and windlass design field tourniquet and has the highest effectiveness rate for prehospital devices.

Pre-Clinical Work Related to Emergency Tourniquet Use

Recent scientific developments have permitted a better understanding of the problem of hemorrhagic shock, hemorrhage control techniques, safety of tourniquet designs, tourniquet effectiveness, and the pathophysiology of ischemia-reperfusion.[8,22-25] The main cause of shock in battle trauma was unclear until the primary role of hemorrhage was elucidated.[26,27] Hemorrhagic shock prevention and treatment has focused mainly on transfusion practices, but tourniquets were occasionally evidenced to control hemorrhage in trauma patients.[19] The safety and effectiveness of tourniquet designs evolved in elective surgery, particularly with the development of pneumatic tourniquets; and the studies indicated that device width and edge shape affected both safety and effectiveness.[23,24,28-36] The gains in knowledge during the past few decades about limb ischemia-reperfusion helped in understanding the risks of tourniquet use, especially the duration of ischemia.[37,38] These multiple and concurrent scientific developments permitted a reappraisal of the burden of injury detailed in the above paragraph on epidemiology so that more tools were available to engineer a solution set to the problem at hand—namely, preventable battlefield deaths from limb exsanguination.[6,8]

Throughout history, many tourniquets of varied designs have been used, such as Petit's screw tourniquet, Morel's block tourniquet, and the strap and windlass tourniquet.[3,8] Many tourniquets have been designed by trial and error from materials at hand without recognition or analysis of the lengthy record of historical designs dating more than 2 millennia; thus, many of the devices we are asked to review are actually similar to prior devices inadvertently reinvented or redesigned. Currently, the standard issue tourniquet for US soldiers deploying to war is the Combat Application Tourniquet (CAT, licensed and manufactured by Composite Resources, Inc, Rock Hill, SC, and distributed mainly by North American Rescue [NAR], Greer, SC). The CAT (National Stock Number 6515-01-521-7976), shown in Figure 14-1, is a strap and windlass design field tourniquet that is 38 mm wide. It has been evidenced in the clinical trial to be the field tourniquet with the highest effectiveness rate (79% of limbs where only a single CAT was used).[3] The hospital tourniquet that was evidenced to have the highest effectiveness rate was the Emergency & Military Tourniquet (EMT, Delfi Medical Innovations, Vancouver, British Columbia, Canada), shown in Figure 14-2. The EMT is a pneumatic tourniquet that is 88 mm wide, which was effective in 92% of limbs with only one EMT used in the clinical trial.[3] The limb segment where ineffectiveness was most was the thigh, which confirms the challenges of compressing larger amounts of tissue as evidenced in the elective surgery literature.[23,24,39] Device design should account for a broad range of knowledge to include anthropometry, safety data, and effectiveness data.[40-45] Specific devices are single-use or designed for reuse. If necessary, a steward for the hospital's emergency tourniquet service should test, clean, and restore devices or remove them from use. Obviously, the steward of a hospital tourniquet service should have adequate experience or training.

Improvised tourniquets usually are strap-and-stick constructs but in practice have included a broad spectrum of items: strings, intravenous tubes, bungee cords, bands (engineer tape), waist belts, screwdrivers, scissors, tree limbs, and rifle cleaning rods. The effectiveness of improvised tourniquets is generally inferior to well-designed tourniquets but measurably better

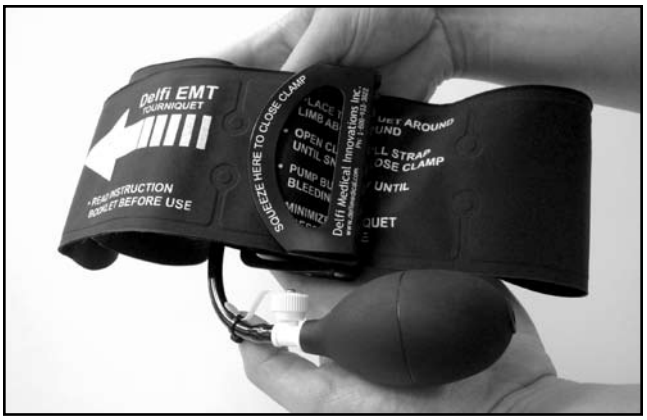

Figure 14-2. Emergency and military tourniquet. Photograph of the Emergency and Military Tourniquet (EMT, Delfi Medical Innovations, Vancouver, British Columbia, Canada; photograph used by permission of Delfi Medical Innovations). The EMT is a pneumatic tourniquet that was the most effective device used in the Army clinical trial.

than no tourniquet at all.[3] The wider improvised tourniquets (cravats and windlass type, especially when 2 were used side by side) were effective in 42% of limbs in the clinical trial, whereas the narrower ones were effective in 25% of limbs. The width of improvised tourniquets has been associated with their effectiveness, which indicates that the width of the device applied to the limb is an important design feature.[3] We have noted that improvised devices often function as venous tourniquets and so are ineffective, and this is particularly true when the device is narrow.

Emergency Tourniquet Use: Implementation, Policy Changes, and Resultant Outcomes

Given a plausible solution to a pressing need, a large-scale fielding of tourniquets to individual deploying US soldiers was executed rapidly in April 2005; and the clinical impact of this logistical and medical effort was prompt and positive.[3,6] Furthermore, the recent emergence of clear and specific needs of those rescuers using tactical combat casualty care has permitted a reconsideration of tenets of such a trauma system, which can differ substantially from routine civilian systems.[13,14,46,47] Recently, Emergency Tourniquet Program leaders for the US Department of Defense ran a large clinical trial in a combat support hospital in Baghdad (National Clinical Trial NCT00517166 at ClinicalTrials.gov). This group reconciled the last resort versus first-aid conflict by changing the question from whether we should use tourniquets to how should we use tourniquets. The compiled subject matter expertise came from the detailed analyses of hundreds of cases from that performance improvement project that has been an academic focus these past few years for us.[3,6,9,15,48-51]

The US Army experience in the current war has shown that if tourniquets are used in casualties at risk of limb exsanguination, the survival rate is higher with use than without use.[6,9] The Army clinical trial has also evidenced that use is associated with longer survival, which permits more life-saving interventions and better resuscitation.[9] The Army trial also evidenced that if the tourniquets are used before shock onset, the majority of the life-saving benefit is maintained and that if the tourniquets are first used after shock onset, then most of the life-saving benefit is lost.[6,9] The trial also evidenced that morbidity with tourniquet use was uncommon, temporary, and minor.[3] Because very few first-aid devices are ever evidenced to improve survival rates, the emergency tourniquet was the prehospital medical breakthrough of the current war.

Clinical Settings for Emergency Tourniquet Use

The main setting is prehospital for emergency tourniquet use in war in that 85% of casualties with tourniquets used emergently have their first one applied before arrival at the emergency department of the first hospital.[3] The remaining 15% have their first tourniquet applied in the emergency department, but experienced providers judged that the entire 15% should have had prehospital use.[3,6] The emergency department of busy military trauma centers acts as the funnel—the one place where the majority, if not all, of casualties in an area flow through. Such an emergency department can accrue rapidly high case counts in an epidemic of war casualties. The Army trial case accrual rate recently was 29 times that of the prior record of the Israelis. Therefore, although most use of tourniquets is prehospital, the experience gained in these referral patterns has been most concentrated in a busy trauma emergency department. The Army trial also evidenced that if the tourniquets are used prehospital, the survival rate is higher than if the first tourniquet is used in the emergency department. This geographic categorization by care setting, however, was a weaker association than the strong physiologic categorization by time of hemorrhagic shock onset.[6,9] The prehospital setting is often where casualties can be treated for their major limb trauma before shock onset; so shock prevention appears to be the main benefit of tourniquet use.[9]

Table 14-1

Current Emergency Tourniquet Recommendations and Findings

If one device does not stop the bleeding, then use a wider device or use 2 side-by-side.
With good tourniquet designs, use on 2-boned segments has the *highest*, not the lowest, effectiveness.
Tourniquet design should account for all relevant science, including casualty anthropometry.
One-handed tourniquet application is desirable but not essential to success in general use.
Different devices have different components that wear or break depending on use or misuse.
Specific devices are single-use or designed for reuse, and the steward should test devices.
Users should understand how devices work best in order to attain optimal outcomes.
Designs should meet user expectations if scientifically grounded by care setting.
When user expectations mismatch the device science, problems abound.
When user expectations match the device science, optimal care is more easily attained.
Leaders should select devices most appropriate for their users based on the best data available.
The steward of a hospital tourniquet service should have experience or training.

Tourniquet Use Indications, Contraindications, and Management in Theater

The indication for emergency tourniquet use is any compressible limb bleeding that the rescuer thinks may be life-threatening; this indication can be categorized into situations or lesions.[52] The main war situational indication is care under fire in that the rescuer and the casualty are under gunfire or similar danger; the benefit of getting the casualty and the rescuer to safety decreases the risk of casualty death and probably rescuer death.[3] Another situation can be mass casualty events where scores of casualties occur at one place and time, such as the incidents at Fort Hood recently and Virginia Tech, and need simultaneous hemorrhage control quickly by a few rescuers.[53] Another situation can be a casualty with multiple injuries who needs hemorrhage control at the same time as other life-saving procedures, such as airway control, when under care of few rescuers.[53] Lesions that indicate tourniquets are major bleeding, often uncontrolled by prior means such as wound compression, limb elevation, or pressure dressings. If one device does not stop the bleeding, then a wider device or 2 devices side-by-side should be used.[3]

The contraindications for emergency tourniquet use are many but are not clearly evidenced. Apparently, many lesions need not have a tourniquet and can be managed by simpler and less risky ways to control hemorrhage. Direct wound compression, limb elevation, or pressure dressings may work, but each of these is not evidenced to improve survival. Limb splinting for an open fracture such as a femur is rarely evidenced to improve survival but may help control hemorrhage and ease transport.[54-56] Wound compression and pressure dressings have sound scientific underpinnings and clearly are popular. They likely have clinical merit although their role has not been delimited clearly, especially for specific lesions or situations.[57,58] Pressure point control of hemorrhage has been studied, but the models are limited and the results have been mixed.[59,60] The real world with situations and lesions being present simultaneously, the difficulty of accurately assessing bleeding (estimating blood loss volume, differentiating arterial from venous bleeding), and the lack of adequate hemorrhage control data sets make differentiating indications and contraindications based on evidence difficult.

The use of tourniquets in emergent settings does not appear to have an obvious effect on the management of the individual casualty later on in the trauma system except for a higher casualty survival rate. A minor effect is a general increase in the severity of injuries to limbs seen in survivors during the span of the war. The injury severity scores for limb-injured casualties surviving to evacuation to the US tertiary care (level IV facility) in Germany has doubled from 2003 to 2007 from 6 to 12, mostly because of the severity of the limb injury. Another minor effect is that the surviving casualties after tourniquet use require more care, like fasciotomy, probably because of the more severe injuries.[3] The rate of fasciotomy has been associated with both injury severity and the duration of tourniquet use.[3] The tourniquet use emergently does have an ischemia-reperfusion phenomenon, but this effect is not obvious and is transitory; there are

many other causes of ischemia-reperfusion in war casualties such as shock, vessel injuries, compartment syndromes, and hypoxia.[3]

Emergency Tourniquet Use Techniques, Misuse, Complications, and Abuse

Analysis of recovered devices provides evidence of how tourniquets should be used and how they should not be used. When recovered devices are systematically analyzed in the context of use as in the clinical trial, it is clear that one-handed tourniquet application is desirable but not essential to success in general use and that hospital devices are neither self-applied nor used one-handedly. Therefore, the specifications of devices should account for a broad range of clinical settings. Forcing the makers of a hospital device to make it self-applied with one hand is a useless constraint not based on any practical need but is just inadvertently constraining hospital device designs to the specifications of ideal prehospital devices.

Designers with special experience use that experience in their designs. For example, a design team with a track record of making ski boot buckles has made a tourniquet that looks similar to such buckles, the Ratcheting Medical Tourniquet [(RMT) sometimes known as the Burke RMT, M2 Inc, Winooski, VT]. A design team that includes a clinical engineer with a long track record of developing surgical tourniquets and generating knowledge on tourniquet use developed a precision instrument, the EMT. Furthermore, tourniquet design should account for all relevant science, including casualty anthropometry, because devices that do not account for the size of the limbs of the casualties do not fit. For example, the US Army Anthropometry study of 1998 gives a good approximation of what the current needs of soldiers are.[61] However, the clinical needs of others, such as children or obese adults, remain plainly different. Device wear analysis indicates that different devices have different components that wear or break depending on use or misuse. In other words, the weakest links vary by design, and how a device is used determines, in part, its effectiveness. Devices that are misused are ineffective. In an example of misuse, if a pneumatic bladder has a needle or knife puncture, then the device fails. Abuse of a device is rare but has included soldiers testing tourniquets on pipes by twisting the devices until the windlass breaks as if there were no consequences to over-twisting and limbs were winch drums of hoisting machines. Over-twisting is needed to make a device effective when the slack is not taken out before twisting, and the taking out of slack is one of the first steps of application after deciding to apply a tourniquet. The users of the devices we have observed and interviewed have tried to apply the devices lightly and with little limb manipulation by not pulling the device tight before twisting (contrary to the written instructions and training), and this inadvertently makes the device less effective and at risk for breakage. The unintended consequence of trying to be gentle is to be late or lethal in failing to control hemorrhage. In general, the order of the steps in application is the order of importance in survival in that the most important is deciding whether to use a device, the second is the time of application, and the third is taking out the slack before tightening. The latter steps are evidently less important to survival.

Emergency Tourniquet Training, Knowledge, and Recurring Misconceptions

There are several important issues concerning the inter-related topics of emergency tourniquet training, knowledge, and misconceptions. The US military has found a cultural difference between how Afghans and Iraqis perform first aid with tourniquets. Afghan soldiers rarely improvise when needed to save lives with tourniquets; and if a bandage or tourniquet is unavailable, they let their wounded comrade die unaided.[62] On the other hand, at the same time, Iraqis improvise tourniquets commonly with any imaginable material while the Afghans rarely did so despite similar materials being available while exposed to the same tourniquet doctrines. In a larger sense, user "cultures" and expectations vary; if users know that hemorrhage control can save lives, that they have practical experience in training and education specifically in how to use tourniquets, and that they have adequate devices or materials, they can and do save lives.[6,9] However, if users have little knowledge, experience, or training, then casualties can frequently die.

US Army training in 2009 is dramatically different than in 2002 regarding tourniquet use. The depth, breadth, and repetition of tourniquet training are more extensive today; and the doctrine, refined through several years of laboratory and clinical research, is more specific and now evidence-based. These widespread training and doctrine improvements are one of the reasons that the casualty survival rate on the battlefield is at an all-time high despite the increasingly severe injuries, particularly to the limbs.[63]

There is a broad knowledge set developed in elective surgery about the principles of tourniquet

use,[25,64] and many of these principles apply to emergency tourniquet use as well.[3] For example, the main tissue vulnerable to the duration of tourniquet use is skeletal muscle, which is the limb tissue most sensitive to ischemia-reperfusion; whereas the main tissue vulnerable to the pressure gradient under a tourniquet is peripheral nerve.[3,65-67]

Despite a broad and growing knowledge base available to tourniquet users, misconceptions persist.[5] Recent articles have produced practical tourniquet findings that have refined training and doctrine, and those refinements appear to be important to performance improvement in trauma systems.[3,5,6,49] However, misconceptions often reappear despite such knowledge production and refinements.[5] A recent 2008 publication perpetuated the 2-bone segment misconception, for example, as the authors reviewed 11 casualties in Boston over 7 years and felt that 2-boned body segments such as the forearm or leg would have less tourniquet effectiveness than 1-boned segments like the arm and thigh.[67] However, given adequate device designs, the 2-boned segments actually have the *highest*, not the lowest, effectiveness; and a large body of knowledge indicates this has been so for some time.[3,5,23-25] The reason this misconception persists is based on an oversimplification: effectiveness is not due to 1 or 2 bones but to a complex relationship among pressure, device width, and limb circumference.[3,23] Another reason that misconceptions recur is that rarely are civilian emergency tourniquet cases compiled for study. The Boston study findings were supportive of more civilian use, but other misconceptions were fostered and not dispelled (the authors noted that pressure was associated with effectiveness but had no consideration of device width or limb circumference; and the authors assumed that observers can reliably tell arterial from venous bleeding without regard for contrary evidence).[68] Users should understand how devices work best in order to attain optimal outcomes. Designs should meet user expectations by care setting if expectations are scientifically grounded because when user expectations mismatch the device science, problems abound. When user expectations match the device science, optimal care is more easily attained.

Emergency Tourniquet Use Doctrines, Policies, Positions, and Algorithms

Trauma systems may or may not have a doctrine (even policies or practices) on emergency tourniquet use. The US military has organized itself to put surgical capabilities forward and close to the point of injury, which is crucial to preventing complications and to translate early prevention of blood loss into improved outcome. The military currently does have a coherent, evidenced-based clinical doctrine on the emergency use of tourniquets; but in the past, the doctrine was unclear and lacked evidence. The US military has taken a trauma systems approach to battlefield survival, and important, long-term efforts of military medics like Sergeant First Class (now retired) Robert Miller of the US Army Rangers and surgeon-leaders like Captain (now retired) Frank Butler of the US Navy and Colonel (now retired) John Holcomb of the US Army help marshal the systematic analysis. Taking a performance improvement strategy, they looked for opportunities to improve casualty survival and helped develop tactical combat casualty care, one of the key differences between civilian and military trauma care. The frequency of tactical casualty care in combat is high, but in civilian care, it is low. Therefore, the military efforts in tactical casualty care took the lead; and the refinement in hemorrhage control by use of emergency tourniquets required an analysis of historical perspective, candidate devices, development of a clear doctrine, an overhaul of training, clinical research, and integrated feedback for system improvement.[13,14]

Despite the growing evidence that limb exsanguination was the leading cause of preventable death on the battlefield upon entry into the current war, there was a need to broadcast that knowledge to key leaders in order to inform the decisions needed for logistical acquisition and fielding of devices. The media and legislative processes helped in the lead up to the decision of the US Army Surgeon General to recommend the issuance of an emergency tourniquet to deploying servicemembers in April 2005. The policy enactment therefore was not with a stroke of a pen but rather was an integrated, complex set of actions aimed at providing a suitable solution. These policies were concordant with the medical evidence that was becoming manifest through the refined doctrine and training.

Organizations that deal with emergency trauma are currently challenged in integrating the new tourniquet knowledge into their policies and practices.[69] For example, some emergency medicine authors have advocated more consideration and study of tourniquet use in civilian settings or have made position statements.[52,70] Some authors have tried to set the use of emergency tourniquets into algorithms in order to simplify the complexities and guide treatment. Examples include the protocols of Taillac and Doyle,[70] which are not developed from any stated data set, and the algorithm developed by the US Army Rangers, which has been developed over several years and many casualties.[71] Each algorithm is aimed at 2 populations

at risk, and the Rangers have their specific and evidenced needs, which are not obviously similar or comparable to the general population at which the other authors aim.

Research Gaps: Dressings, Pressure Points, and Proximal Bleeding

Future directions for research are numerous as there are many items to confirm, develop, or refine. Tourniquet alternatives including elevation, pressure dressings, and pressure points are without clear and practical data sets evidencing hemorrhage control; so these are candidates of further study. Enough data have been published recently to consider decision analysis, medico-legal, or actuarial studies or models of emergency tourniquet use in order to model whether or how they are used. Such study may help trauma system leaders decide whether their system's constituents need tourniquets available or whether they know how best to use them.

If tourniquets solved the limb exsanguination death problem after we picked it as the lowest lying fruit in combat casualty care, then the next fruit to be picked requires a longer reach. Bleeding from very proximal extremities may require new or different tourniquets in order to compress the groin or axilla because conventional tourniquets are less effective there. We currently label such *hemorrhage junctional bleeding*. Similarly, abdominal or aortic tourniquets may be studied in order to determine if or when these devices might be used to gain hemorrhage control.[60,72]

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