

**Traumatic Foot and Ankle  
Injuries Related to Recent  
International Conflicts**

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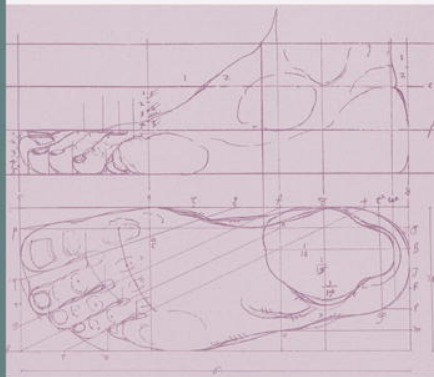
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# Use of Tourniquets and Their Effects on Limb Function in the Modern Combat Environment

John F. Kragh Jr, MD

## KEYWORDS

- First aid • Hemorrhage control • Resuscitation
- Mass casualties • Disaster

First aid innovations in the current war have brought new lessons on casualty care with obvious differences between routine civilian and military casualty care regarding emergency tourniquets.<sup>1-3</sup> The modern battlefield emergency tourniquet is a major prehospital treatment advance of the current war.<sup>4</sup> The current standard-issue emergency tourniquet is an award winning Army innovation of 2005. The use of this device in saving soldiers' lives on the current battlefields has been so widespread that its use has spilled over to help save the lives of wounded civilians within the war zone. In one of the more publicized examples, CBS News foreign correspondent Kimberly Dozier recently reported that it was "...tying on the tourniquets that saved my life"<sup>5</sup> after she suffered severe injuries in an improvised device explosion in Baghdad on Memorial Day 2006. A fresh look at the reasons why tourniquets have proved lifesaving is due. New knowledge can help clinicians decide when and how to use them in a multiply injured casualty or in the case of mass casualties.

## THE IMPORTANCE OF NEW EMERGENCY TOURNIQUET USE

Orthopedic surgeons are the main care providers receiving casualties with emergency tourniquets recently applied. Many have extensive predeployment experience with

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tourniquets used for elective surgeries. As such, they are the subject matter experts on tourniquets, and receive the most questions on their use and misuse. Severe limb injuries can be lethal; tourniquet use can be lifesaving if used properly, or morbid if used improperly.<sup>3</sup>

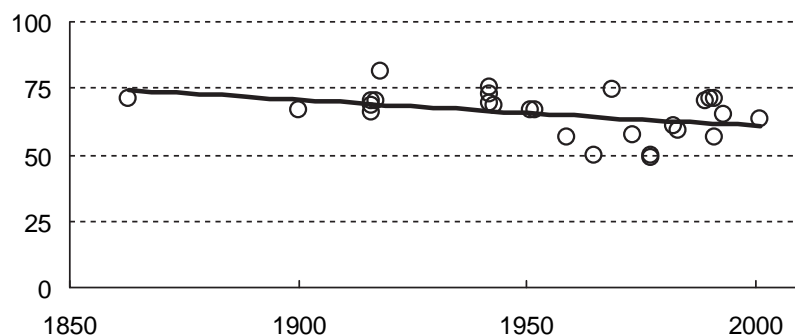
## EPIDEMIOLOGY: INCIDENCE OF TOURNIQUET USE

A recent study of the emergency room of the combat support hospital in Baghdad's International Zone demonstrated that 18% of trauma admissions had emergency tourniquets applied.<sup>2</sup> That Baghdad case accrual rate was 29 times faster than any prior report.<sup>2,6</sup> Another recent military study from the United Kingdom reported 5% of battle casualties had tourniquet use.<sup>7</sup> These data are rare; many trauma systems do not track tourniquet use or death rate from limb exsanguinations.<sup>8,9</sup>

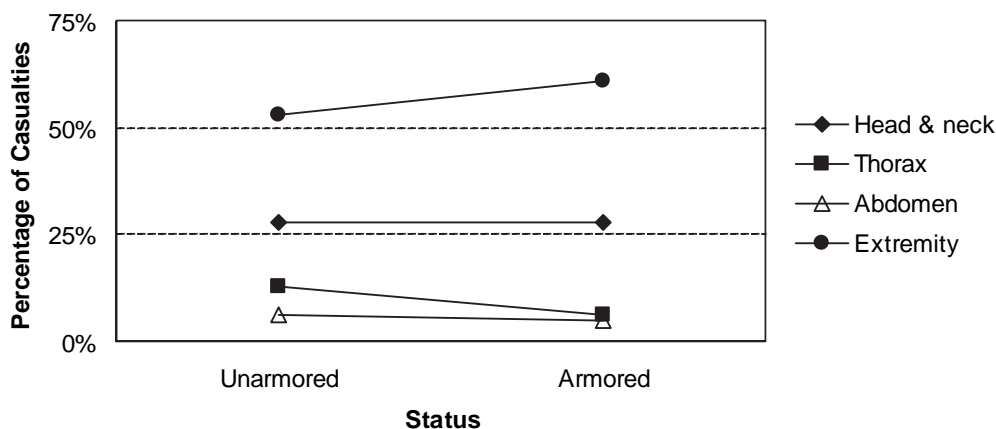
At Brooke Army Medical Center, San Antonio, Texas, which serves as both a military and civilian trauma center, at least six civilian trauma patients in 2007 and 2008 had emergency tourniquets used. The trauma registry does not systematically record tourniquet use, so underdetection is likely. The tourniquets used in San Antonio were placed by lay bystanders at the point of injury, by paramedics in the field, and by nurses and surgeons in the emergency room.

In the current conflicts the rates of body regions sustaining penetrating trauma are approximated by the exposed body surface areas, and the extremities are about 61%. This mirrors the rate of limb trauma in most modern wars (**Fig. 1**).<sup>10,11</sup> Lower limb injury rates are about 26% to 48% of total casualties in modern wars,<sup>12,13</sup> which approximates the lower limb exposed body surface area.<sup>10</sup> In a recent Baghdad study, 73% of limb injuries that met criteria for proper tourniquet application were in the lower limbs<sup>2</sup> and this proportion approximates the lower limb proportion of the upper and lower limbs exposed body surface area. Emergency tourniquet use is common in those with foot and ankle injuries.<sup>2</sup>

Protection by body armor increases survival of casualties with head and torso injuries. These survivors often have additional limb injuries. Casualty data indicate that limb injuries in survivors increase 7% after the introduction of torso armor (**Fig. 2**).<sup>14,15</sup>



**Fig. 1.** Percentage of war casualties surviving to the first hospital with extremity injuries. The proportion of casualties with limb injury is about 61%, the proportion of body surface exposed to penetrating trauma. The proportion of casualties arriving alive at the hospital with limb injuries has decreased slightly over the decades probably because evacuation became faster later so more head and torso injured casualties survived to hospital. (From Burns BD, Zuckerman S. Fragmentation panel of the static detonation committee, advisory council on Scientific Research and Technical Development. Ministry of Supply, United Kingdom, RC350, 1942.)



**Fig. 2.** Percentage of casualties by body region before and after torso body armor. Military units that reported the percentage of casualties by body region before and after fielding torso body armor measured a 7% increase in limb injuries and a 7% decrease in torso injuries. (Data from Holmes RH. Wound ballistics and body armor. JAMA 1952;150:73-8; with permission; Holmes RH, Enos WF Jr, Beyer JC. Medical aspects of body armor used in Korea. JAMA 1954;155:1477-8.)

The lifesaving benefit of tourniquets,<sup>3</sup> improved resuscitation of casualties,<sup>16,17</sup> and refinements of the casualty trauma system have improved the survival rate of United States military casualties to an all-time high.<sup>18</sup> Limb salvage rates are now high with modern vascular surgery using damage control principles.<sup>19,20</sup> The historical adage of “life over limb” has to be invoked less frequently as recent experience indicates that most of the time, both can be achieved in the modern battlefield casualty.<sup>1-3,19,20</sup>

With modern armor protection, a high rate of lower limb wounding, lifesaving use of tourniquets and resuscitation, and high limb salvage rates, foot and ankle surgeons and providers are likely to see casualties early in emergency care, during reconstructive stages, or late in rehabilitation or aftercare.

## HEMORRHAGE AND MORTALITY

Before widespread, proper tourniquet use uncontrolled hemorrhage through a wounded extremity was the most common cause of preventable death on the battlefield.<sup>21</sup> It is the second leading cause of death in civilian trauma after head injury.<sup>22-24</sup> Exsanguination from a limb wound constituted about 9% of United States combat deaths in the Vietnam War.<sup>21</sup> With more frequent tourniquet use in the wars after Vietnam, the rate of limb exsanguination death decreased such that the rate currently is 2% in United States casualties.<sup>25-28</sup> The Israeli Defense Forces, the most avid users of tourniquets, recently reported overuse in 2003 (47% were not indicated); however, they had a 0% limb exsanguination death rate.<sup>6</sup> These findings indicate that there is a direct correlation between tourniquet use and survival in major limb trauma, but the rate of optimal use is unknown. The morbidity rate with emergency tourniquet use by the United States military, which has a comprehensive approach to training, has been low as detailed later.<sup>2</sup>

Battle casualties with open fractures or traumatic amputations can undergo substantial hemorrhage often requiring massive transfusion.<sup>29-36</sup> The quantity of transfusion in these patients may be the greatest of all casualties surviving to the first hospital.<sup>30,37</sup> Bleeding in those with major limb injuries is not limited to that observed at one point in time by one provider. Hemorrhage may occur at the injury scene, throughout extrication, transport, emergency bays, operating theaters, and intensive

care wards.<sup>29</sup> The amount of blood lost from limb injured casualties is commonly underestimated.<sup>29,30,37</sup> Before seeing a limb-injured casualty with massive hemorrhage, providers often have difficulties realizing that these patients may have more immediate hemorrhage control and blood replacement needs than head- and trunk-injured casualties. Educating providers about the need for hemorrhage control and blood replacement in limb casualties needs to be an early goal of the deployed trauma surgeon.

Exsanguinations in injured civilians may also be preventable.<sup>38,39</sup> A 5.5-year study out of Houston noted 14 of over 75,000 emergency center casualty visits were candidates for tourniquet use. Eight of the 14 casualties exsanguinated.<sup>9</sup> Similarly, in the United Kingdom, a study of 1000 trauma deaths revealed 71 from penetrating trauma. One of these had an exsanguination (radial artery laceration) amenable to prehospital tourniquet use.<sup>8</sup>

## **SURVIVAL RATES AND HEMORRHAGE CONTROL**

Hemorrhage control in casualties is associated with less blood loss, less need for transfusion, and improved survival.<sup>37</sup> Lack of hemorrhage control is associated with death.<sup>37</sup> The easiest way to gain control of substantial limb bleeding in battle casualties is by tourniquet use as long as the bleeding is compressible.<sup>37</sup> A study conducted during Operation Iraqi Freedom showed that tourniquets effectively control hemorrhage,<sup>1</sup> and another showed that they improve survival.<sup>3</sup>

Animal data indicate that tourniquets used emergently to control hemorrhage prevent shock onset,<sup>40</sup> and battle casualty data indicate that this is the case if used promptly.<sup>3</sup> If used after shock onset, most of the survival benefit is lost.<sup>3</sup> Limb hemorrhage control by tourniquet use permits more effective resuscitation.<sup>37</sup> Furthermore, tourniquet use lengthens the survival time and provides more time for resuscitation or other lifesaving interventions.<sup>3</sup> These data indicate that tourniquets prevent shock onset if used promptly for hemorrhage control in bleeding casualties and may prevent the worsening of shock. Furthermore, hemorrhage control with tourniquets decreases transfusion needs and resuscitation risks<sup>37</sup> while improving limb salvage rates.<sup>19,20</sup>

A recent investigation at the Institute of Surgical Research showed that susceptibility of rats to die from hemorrhage is widely variable. About half of the risk seems to be caused by heritable variability, with the other half caused by environmental factors. Given the same quantity of blood loss in different rat strains, mean survival times varied 7.7-fold.<sup>41</sup> Currently, no human genetic markers indicate which casualties are apt to survive hemorrhage. Perhaps genetics may affect tolerance to tourniquet ischemia-reperfusion, which is also widely variable. Also, environmental factors, such as hydration status, fitness level, and age, may affect tolerance.

## **PREHOSPITAL CARE**

In a recent study within the Baghdad Combat Support Hospital about 85% of battle casualties with (one or more) tourniquets had the device applied before arrival to a facility (prehospital tourniquet), and the remaining 15% had their first tourniquet applied in the hospital (hospital tourniquet). Lay persons, soldiers, soldier-medics, civilian contractors, policemen, nurses, physician assistants, physicians, and surgeons applied the devices, but most seemed to be applied by soldiers and medics.<sup>2</sup> Medics and nurses applied most tourniquets under physician guidance in the emergency department.

## **EMERGENCY DEPARTMENT CARE**

According to the military hospital providers in Baghdad in a recent study, all of the 15% of casualties with their first tourniquet applied in the hospital should have had application prehospital.<sup>1,2</sup> Additionally, there was a 5% unindicated (12 of 232) use rate but a 2% miss rate (5 of 232). The miss rate was the casualty death rate for those indicated for tourniquet where a tourniquet was inaccessible or unavailable.<sup>2</sup> The previously mentioned Israeli study had a 47% unindicated use rate.<sup>6</sup> These findings reveal that most battle casualties for whom tourniquet use is indicated should have them applied prehospital, and that the indications for use need refinement, improved user education, and better device fielding. Although physicians often direct care, those who actually apply the devices have limited or no formal medical training. Application of military tourniquets has been mandatory entry-level training for every United States service member for several years. Universal retraining recurs before and occasionally during deployments. Those applying tourniquets before hospital arrival need practical guidance.

The exchange of a prehospital tourniquet for a hospital tourniquet was done often in the Baghdad studies because the latter are wider, more effective, and safer than the former.<sup>2</sup> The release of a prehospital tourniquet allows assessment of hemorrhage control possibly shortening ischemia time, one factor in decreasing tourniquet risk. Successful placement of a pressure dressing was common in the emergency department, but a substantial proportion of casualties failed a trial of tourniquet removal and required surgery to control hemorrhage.<sup>1</sup>

If one tourniquet was ineffective in controlling hemorrhage, then a second was commonly used adjacent to the first. This increased effectiveness from 82% to 92% and was likely caused by increasing the width of the compressed tissue and artery proximal to the wound.<sup>2</sup>

## **OPERATING ROOM AND INTENSIVE CARE**

In civilian settings, surgery is frequently the main cause of blood loss, but on the battlefield it is penetrating trauma.<sup>21,42</sup> Together, losses from trauma and surgery may require more tourniquet use in the operating room. Although use of tourniquets in elective surgery is common, surgeon knowledge of tourniquet science is limited.<sup>43,44</sup> The resuscitative context of emergency tourniquet use differs from elective use in that the preinjury medical history or peripheral vascular status of the casualty may be unknown. The ischemia-reperfusion effects on the injured limb caused by tourniquet use is complicated by limb wounds, hypoxia, hypotension, shock and hypoperfusion, resuscitation, coagulopathy, vascular ligation or repair, associated injuries, or complications.

## **INDICATIONS FOR EMERGENCY TOURNIQUET USE**

The current indication for emergency tourniquet use is any compressible limb wound that the applier assesses as having potentially lethal hemorrhage. In this environment tourniquet use may be the initial and primary method to control severe hemorrhage. This is in contrast to a historical stepwise approach that used application of direct pressure and pressure points to control hemorrhage before tourniquet application.

Such situations as care under gunfire are routine in combat where the tourniquet is used initially to free up individuals to perform other imperative tasks. Once the tourniquet is applied the caregiver can then defend the unit, aid other casualties, or help the casualty move to safety. This is an example of true first-aid. Another advantage is that successful tourniquet application allows the individual providing



care to undertake concurrent resuscitative procedures in the multiply injured casualty. Mass casualties may also be a situation for tourniquets. In the Baghdad studies, a large proportion of casualties had more than one indication (eg, care under fire with life-threatening limb bleeding); only 5% had no indication.<sup>2</sup> In the civilian environment recommendations for considering selective tourniquet use have been put forth by authors, academic clinicians, and trauma organizations, and it is now more common to see tourniquets in civilian ambulances and used in civilian trauma centers.<sup>9,45–48</sup>

## CONTRAINDICATIONS

Currently, there are no data that clearly show contraindications to emergency tourniquet application. Without any situational indication, however, bleeding lesions controlled by simpler, safer means are theoretically a contraindication to tourniquet use. Such means may include direct wound pressure, a pressure dressing, limb elevation, pressure point compression, or hemostatic dressings. The effectiveness of such methods, however, is lacking or unconvincing.<sup>45</sup> Swan and colleagues<sup>47</sup> reported data that pressure point compression occludes distal arterial circulation for less than 41 seconds because of collateral circulation, and that so-called “pressure point control” of extremity arterial hemorrhage is a euphemistic misnomer.

The speed of hemorrhage control may be vital in lesions near the groin or axilla. In these regions the speed of application of nontourniquet hemostatic methods may be too slow. There are reports from the field of exsanguination from groin arterial injuries within approximately 60 seconds.<sup>49</sup> Instances of such rapid exsanguination, however, are rarely reported.

One cohort study gives some data that traumatic amputations seen at a field hospital may be contraindicated for tourniquets when care is not under fire; however, the tourniquets were improvised (not scientifically designed) and there was no tourniquet doctrine or training, but the evacuation times were long, which has been associated with complications caused by prolonged use.<sup>50,51</sup>

## GOALS OF CARE

Care goals of emergency tourniquet use can be seen as hemorrhage control, shock prevention, improved survival rates, lengthening survival times, elimination of distal pulses, and limb salvage rates. The immediate aim of the applicant is to stop bleeding, thereby making the other goals attainable; however, hemorrhage control may be temporary if the distal pulse persists. When a distal pulse is present in a limb with a tourniquet, it is a venous, not arterial, tourniquet, and problems soon arise.<sup>2,44</sup> With each systole blood is driven into the distal limb and lost to the core circulation. Shock onset is hastened or worsened by such core blood loss. Pooling of blood distally engorges veins leading to limb congestion and more severe edema. Bleeding can increase with the onset of venous hypertension. Distal to the venous tourniquet, expanding hematomas and development of compartment syndrome can lead to a need for more extensive debridement or fasciotomy, respectively. Mortality rates have been shown to increase with venous tourniquet use.<sup>2</sup> Survival rates, survival times, and limb salvage rates<sup>2,19,20</sup> are better with modern tourniquet use but are worse with improvised tourniquets,<sup>50,51</sup> so tourniquet design seems important to survival. Elimination of pulses distal to the tourniquet decreases these problems in both emergent and elective tourniquet use.<sup>2,44</sup>



## DESIGN

Tourniquet design affects ease of use, durability and mechanical effectiveness (stopping bleeding and ridding the distal pulse). Weight, cost, durability, simplicity, packaging volume, and user expectations are other design considerations. Improvised and poorly designed tourniquets are suboptimal, and the best tourniquets require consideration of tourniquet science and human factors.<sup>2</sup> One of the most important design features concerning effectiveness is tourniquet width.<sup>44</sup> Those without knowledge of tourniquet science often think that pressure is the main determinant of effectiveness, not realizing that pressure risks nerve palsy, whereas greater width allows hemostasis with less pressure.<sup>44,52-54</sup> Arterial occlusion pressure can be determined by ultrasonic flowmetry. The occlusion pressure is inversely proportional to the ratio of tourniquet cuff width to limb circumference and is in the subsystolic range at a ratio above 0.5. Wide tourniquet cuffs, such as those used in surgery, can achieve an effective arrest of the regional arterial circulation at subsystolic pressures of inflation. The ratio rises nearly asymptotically vertical below 0.08.<sup>53,54</sup> As the user tries to increase pressure by tightening a tourniquet, the pressure can soon damage nerves (>500 mm Hg) while remaining ineffective. Many tourniquet manufacturers are unaware of the body of knowledge and publications.<sup>44,52-54</sup> The best prehospital tourniquet in a recent Baghdad study was the combat application tourniquet (CAT, North American Rescue Products, Greer, South Carolina) (Fig. 3). The CAT was 100% effective in laboratory testing and 79% effective in emergency use.<sup>2,55</sup> The CAT is 38 mm wide and was selected as the standard issue military tourniquet in 2005. The CAT is a strap and stick design, which is the most common design expected by lay persons and soldiers so it is simple to use. The CAT is also small, light, inexpensive, durable, and easy with which to train. This device was named a top Army innovation in 2005. An even more effective tourniquet used in Baghdad was the emergency medical tourniquet (EMT, Delfi Technologies, Vancouver, British Columbia, Canada), which is a pneumatic design not dissimilar to a blood pressure cuff. The EMT is 88 mm wide and was



**Fig. 3.** Combat application tourniquet (CAT). The combat application tourniquet (*Courtesy of North American Rescue Products, Greer, South Carolina. Copyright © 2009 North American Rescue Inc. Used with permission.*) is a strap and windlass design. Its current version now includes a red tip for the main, black strap, and white retainer strap that includes an area to write the time of application. The civilian model is rescue orange in color, the trainer model is blue, and the tactical model is black.

100% effective in the laboratory and 92% effective in the emergency department, but it is heavy, large, expensive, fragile, and requires more training. Hospital providers find this device practical, but lay persons can find it confusing on first use.

For over five decades, the United States Army used a standard issue, cotton-strap and buckle tourniquet (past National Stock Number [NSN] 6515-00-383-0565 and no longer available). It lost tension during application rendering it ineffective on thighs as it had no mechanical advantage like the CAT, a strap and windlass device. The US Army used this tourniquet in World War II; it was often ineffective at controlling arterial bleeding, and later testing showed that it could not stop the arterial pulse reliably in thigh use.<sup>56,57</sup> This inadequate design may have contributed to the widespread feeling that tourniquets were ineffective. Recent testing funded by the US Special Operations Command in 2002 proved the old Army tourniquet was ineffective. The objective data generated from these studies helped replace it and ensured that it was removed from the supply system (**Box 1**). The replacement device (CAT NSN 6515-01-521-7976) has been proved effective by laboratory analysis, field testing, and clinical use.<sup>2,57</sup>

### **TOURNIQUET USE, TISSUE ISCHEMIA, AND LIMB FUNCTION**

Skin, bone, tendon, fat, fascia, joints, and vessels tolerate ischemia and reperfusion better than muscle tissue. Myocytes are much more susceptible to the ischemia and reperfusion effects associated with prolonged tourniquet use. Ischemia-reperfusion myopathy is inadequately studied especially in recovery, but animal data indicate that the muscle necrosis incurred recovers incompletely over several days.<sup>58</sup> Having followed hundreds of casualties whose treatment involved tourniquet use (some for greater than a year), the author found that the ischemia-reperfusion dysfunction was not clinically discernable or separable from that of the wound (eg, fracture). This cast doubt on the possibility that the sequelae of injury may be worsened by tourniquet use. The exception was the 1.4% that had tourniquet palsy. Tourniquet palsies, however, were incomplete, minor, and temporary. Major limb shortening (ie, loss of a knee or major joint) was rare in the Baghdad studies and was associated with multiple causes of which prolonged tourniquet use was only one.<sup>2</sup> The incidence of such shortening was 0.4% and was often attributable to several reasons (injury, prosthetic fitting, flap failure) more so than to the tourniquet. Nontourniquet casualties seem to have the same function as those who had tourniquet use. The only obvious effects of tourniquet use measured to date is that casualties are surviving more often despite worse injuries.<sup>2,3,59</sup> The proportion of casualties with major limb trauma

#### **Box 1**

##### **Venous tourniquet problems in order of their clinical appearance**

Persistent distal arterial pulse with continued core blood loss with each pulsation

Distal venous distention, engorgement, and venous hypertension

Distal blood pooling, expanding wound hematomas, and need for wound debridement

Loss of plasma from circulation into tissues distally and distal limb swelling and edema

Increased pressure in distal tissues risking compartment syndrome, necrosis, and fasciotomy

More hemorrhage often paradoxically worse than with no tourniquet and difficult to control

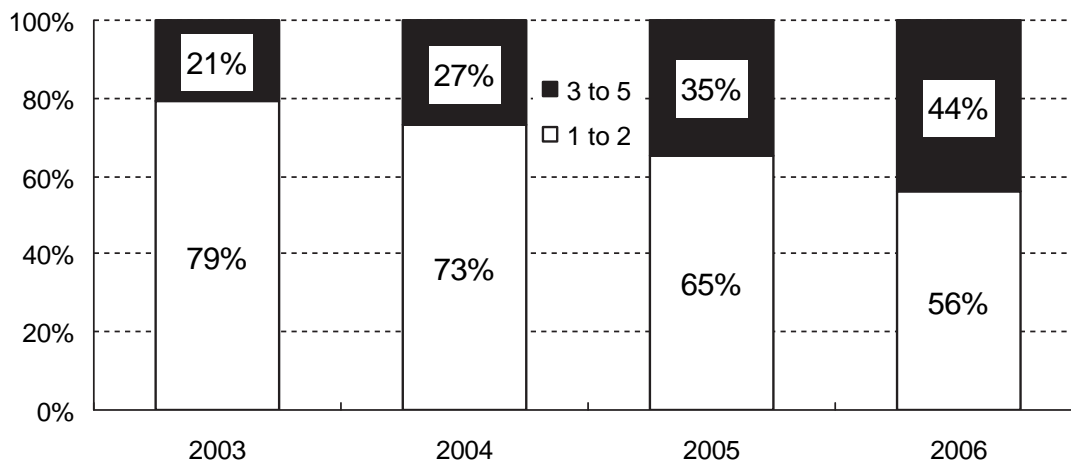
Shock from hemorrhage and hypovolemia

Death

(Abbreviated Injury Scale 3 or more) during the current war has more than doubled from 21% in 2003 to 44% in 2006 (Fig. 4). Data to date indicate no increased organ failure, thromboses, emboli, or myonecrosis compared with casualties injured in similar severity, whereas casualties with tourniquets rarely have major limb shortening (loss of a major joint) or tourniquet palsy, the two morbidities most associable with tourniquet use.

## RECONCILIATION OF HISTORICALLY BAD EXPERIENCES WITH CURRENT SUPPORTIVE EVIDENCE

Historical experience with tourniquets has been so bad that they were often banned.<sup>44,51,60,61</sup> The United States military's recent tourniquet experience may seem like a quixotic triumph of hope over experience. It is actually the result of a comprehensive multifaceted program, however, aimed to solve preventable deaths on the battlefield (Fig. 5). Good judgment comes from bad experience, and the key to reconciling the disparate experiences was in the question asked. Whether one should use a tourniquet or not is a simple binary, yes-no question, whereas best care of severe life-threatening limb injury is complex. The best care for casualties that need tourniquets requires the right devices designed in accordance with current science, used according to refined doctrine after modern training of users, and used at the right time with rapid evacuation. This combination has improved survival after combat injury.<sup>1,3</sup> Proper devices, doctrine, training, and use seem to be essential to best care, and lack of any leads to bad results. Most tourniquet knowledge is new because most publications in the Medline database are recent (Fig. 6). Designs now are more scientific, the width-effectiveness issue is better understood, and the pressure-nerve injury relationship is more established. Poorly designed or outdated devices are now less commonly seen in use. Past bad tourniquet experiences are now explicable because prior science, device designs, training, doctrine, and evacuation were inadequate. All these essentials have been improved recently. The Joint Theater Trauma System in the current war has as its motto, "The right care to the right casualty at



**Fig. 4.** Proportion of casualties with major limb trauma in the current war. The proportion of casualties with major limb trauma (Abbreviated Injury Scale 3 or higher) in the current war has doubled from 21% to 44% from 2003 to 2006. Tourniquets were introduced widely on April 1, 2005. The injury severity scores for these casualties also doubled (6–12). The survival rate remained steady, however, at an all-time high because of the lifesaving benefit of tourniquets.

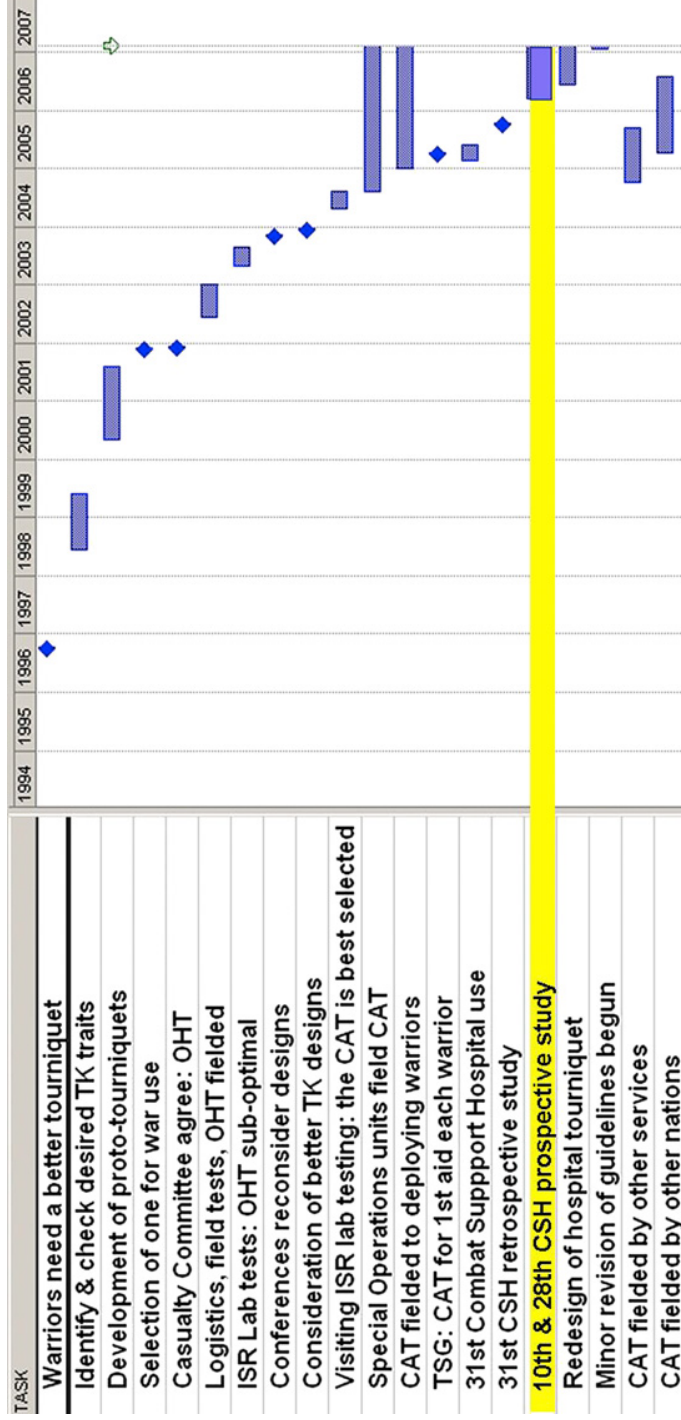
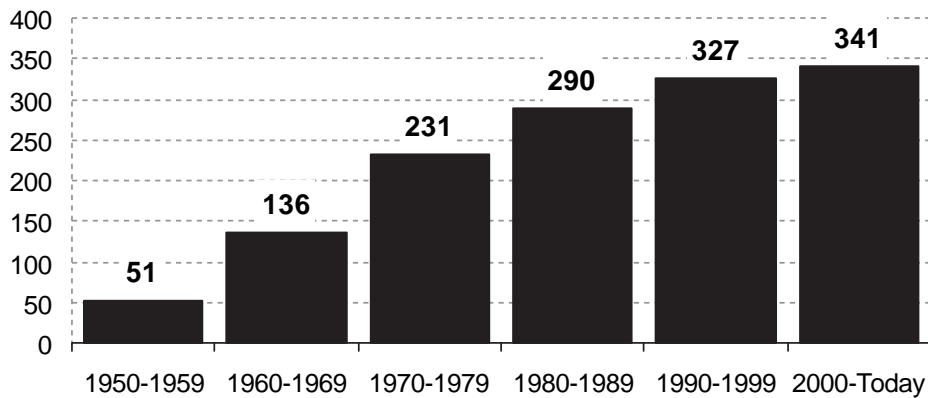


Fig. 5. Gantt diagram outlining major recent items in tourniquet research and development. Much tourniquet research and development is new. Baghdad's big clinical trial is highlighted. CAT, combat application tourniquet; CSH, combat support hospital; ISR, Institute of Surgical Research; OHT, one-handed tourniquet; TK, tourniquet; TSG, The Army Surgeon General.



**Fig. 6.** Number of tourniquet publications by time period. Most tourniquet knowledge is new. Most publications in the Medline database titled with the word tourniquet are recent.

the right location and right time.” This is labeled its R4 motto, and tourniquets are its exemplar.

### USE DURATION, DOCTRINE, AND TRAINING

Tourniquet use is simply a component of damage control orthopedics.<sup>62</sup> For a casualty, temporary tourniquets control hemorrhage, prevent shock, and save lives allowing resuscitation to be effective.<sup>3</sup> Tourniquet on and off times should be recorded so that the duration of tourniquet use can be calculated. Using an indelible marker to mark the time of application on the casualty’s forehead permits the surgeon to know how long the tourniquet has been on. Subtracting the off time (observed directly or recorded in hospital record) from the on time yields the duration. Only 14% of casualties had both the on and off times recorded on the casualty or health care record in accordance with doctrine in a recent Baghdad study, so improved compliance is needed.<sup>2</sup> Treating providers should record pertinent data for aftercare.

Most (91%) tourniquet use in Baghdad was 2 hours or less with low risk of complications. Surgeon willingness to perform fasciotomy seemed to increase with longer tourniquet durations. Warm ischemia time of greater than 8 hours increases ischemia-reperfusion complications, particularly myopathy, but data indicate the risk is limited.<sup>2,59,63</sup> The temporal relationship of cool ischemia time to complications does not seem to have such a well-defined relationship.<sup>59,63</sup> The distal extremities, such as the hand and foot, have relatively few myocytes so they tolerate ischemia better than thighs or arms where muscle tissue volume is high. Digits (no skeletal muscle) tolerate ischemia the best. Muscles that are predominantly slow twitch (type II) are more tolerant of ischemia than fast twitch muscles.<sup>58</sup> For prolonged use (>8 hours) little evidence is available to guide treatment. No therapeutic ischemia-reperfusion posttreatments (tris[hydroxymethyl]aminomethane, bicarbonate, and so forth) have been well studied. Monitoring of plasma potassium, acidosis, myoglobin, and enzymes (creatinine kinase, lactate dehydrogenase) may be useful to detect or monitor myopathy during treatment to prevent acute renal failure. Some data indicate that tourniquet use and prolonged warm ischemia time risks distal limb swelling after tourniquet release as plasma leaks from muscle enough to cause late-onset hypovolemic shock and eventually death.<sup>64</sup> Animal data indicate that death may ensue several hours subsequent to tourniquet release after very prolonged warm ischemia because of hyperkalemic cardiac arrhythmia.<sup>65</sup> Surgical amputation after very prolonged tourniquet use seems prudent if the warm ischemia time is very long, but the temporal threshold is unknown. Cool, acidotic blood recirculated after tourniquet



release may exacerbate coagulopathy and other problems, but data in support of this are limited. The capacity of ischemic tissue to recover is often better than clinicians suspect, and apical tissue, such as digits, can recover well without need for amputation after prolonged ischemia.<sup>59,66</sup>

## EFFECTS ON TISSUES UNDER TOURNIQUETS

The tissue most susceptible to the pressure tourniquet impart is peripheral nerve. The location at which nerves are most affected are at the edges of the device; this coincides with the point of maximal tissue pressure gradient. Nerve tissue under the proximal edge of the tourniquet is more susceptible than that at the distal edge. This steep pressure gradient is spatially associated with a specific nerve deformation morphologically similar to that seen with intestinal intussusceptions. The axonal deformation includes displacement of the node of Ranvier from its normal site with stretching of the paranodal myelin on one side of the node and invagination of the paranodal myelin on the other. The nodes of Ranvier are displaced along the gradient such that the axon telescopes into its contiguous part adjacent not under the tourniquet. This deformation precedes paranodal demyelination. The degree of deformation is directly proportional to the magnitude of the pressure gradient, which implies a cause and effect relationship.<sup>52</sup>

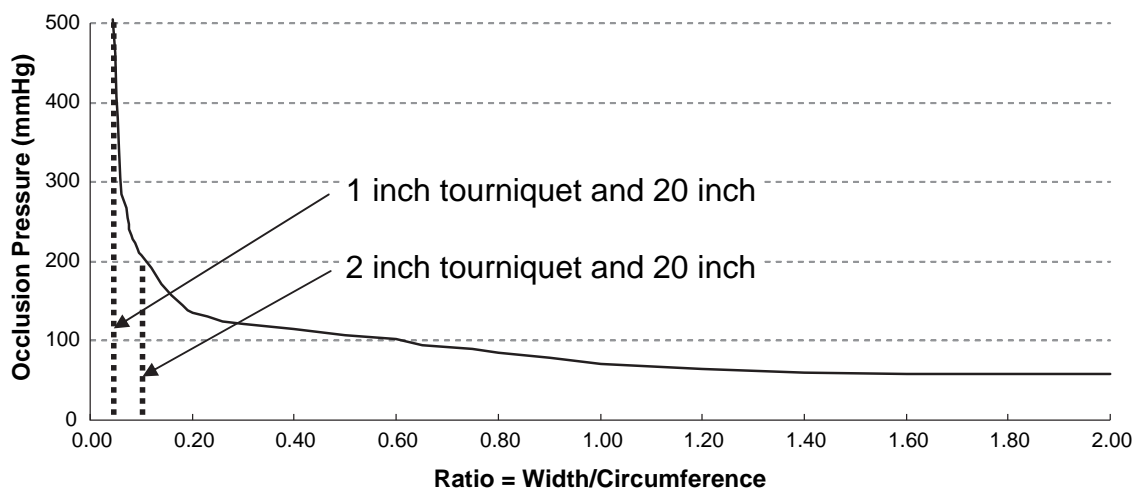
Tourniquet palsy is uncommon during either elective surgery (1:5000 upper extremities and 1:13,000 lower extremities) or in emergent situations (6:162 upper extremities and 9:503 lower extremities).<sup>67</sup> Although uncommon, when present tourniquet palsies are most often incomplete and temporary. In the Baghdad experience tourniquet palsy is twice as likely in the brachium as the thigh probably because the smaller limb girth allows transmission of higher tourniquet pressures.<sup>2</sup> Tourniquet palsies are temporary 98% of the time.<sup>67</sup> The most common manifestations are weakness and decreased sensation. When they develop from emergent use, palsies are not routinely noticed by casualties but detected only by experienced clinicians. Increased risk with prehospital use (users with less knowledge or training) indicates that the quality and quantity of training may decrease this complication. Effectiveness of tourniquets is mostly related to width, so if one does not control hemorrhage, another tourniquet added adjacent to the first has been shown to increase clinical effectiveness from 82% to 92% (**Fig. 7**).<sup>2</sup> Additional tourniquet placement proximal to one initially applied effectively widens the area of compressed tissue. Increasing the pressure of a previously applied tourniquet that is not stanching hemorrhage is unlikely to work with narrow devices, however, and risks nerve injury (**Fig. 8**). Very wide tourniquets as used in elective surgery can occlude arteries at subsystolic pressures.<sup>53,54</sup> Few prehospital providers understand that increasing absolute tourniquet pressure is not the safe way to gain effectiveness; increasing effective tourniquet width is the safe way.

A number of tourniquet-related complications have been described in the civilian arena. These include pressure sores, chemical burns and blistering, thrombosis, post-tourniquet syndrome, intraoperative bleeding, digital necrosis, and toxic reactions to local anesthetics administered distally to the point of tourniquet application.<sup>68,69</sup> Tourniquets applied with too little pressure also risk substantial complications (loss of hemorrhage control) and tissue damage. Venous tourniquets represent occlusion of the venous vasculature without arterial occlusion. The effect of venous tourniquets is delivery of arterial blood to the tissues without sufficient venous return. The multiple adverse effects and their potential outcomes from venous tourniquets are listed in **Box 1**. Loose tourniquets are ineffective and may lead to morbidity or death.<sup>2,3</sup> Reassessment of casualties and tourniquets is vital because casualty transportation and limb manipulation risk tourniquet loosening.



**Fig. 7.** Tourniquets used side-by-side. This casualty has two CAT tourniquets used side-by-side on the thigh, the limb segment with the greatest circumference. Side-by-side use effectively makes the tourniquet width greater, which helps improve the capacity to stop hemorrhage by compressing the arteries better. This case is described in detail elsewhere. Tourniquets placed side-by-side increases the effective width of application. Increasing tourniquet width is much more effective at stopping hemorrhage than increasing tourniquet pressure. (From Kragh JF Jr, Walters TJ, Baer DG, et al. Practical use of emergency tourniquets to stop bleeding in major limb trauma. *J Trauma* 2008;64:S38–50; with permission.)

Improper location of placement may also lead to complications. Distal use does not control hemorrhage from proximal lesions; such use is lethal.<sup>2,3</sup> The US Army Rangers adopted proximal tourniquet placement in the groin and axilla to avoid placement distal to occult injuries. Ranger standard operating procedures for tourniquets were codified in their 2007 medic handbook and recently became doctrine.<sup>70</sup>



**Fig. 8.** Arterial occlusion pressure graphed versus ratio of tourniquet width to limb circumference. The pressure required to occlude arteries is related to the ratio of tourniquet width to limb circumference. As the width-to-circumference ratio decreases, the pressure rises dramatically. Safe pressure is limited to 300 mm Hg routinely, and nerve injury occurs at 500 mm Hg. Wider tourniquets reach effective pressures more easily than narrow ones, and very wide tourniquets are effective at subsystolic pressures. (Adapted from Graham B, Breault MJ, McEwen JA, et al. Occlusion of arterial flow in the extremities at subsystolic pressures through the use of wide tourniquet cuffs. *Clin Orthop* 1993;286:257–61; with permission.)



## STEWARDSHIP TASKS OF THE EMERGENCY TOURNIQUET PROGRAM

Lessons learned in the Baghdad Combat Support Hospital can contribute to disaster planning. The goals of its emergency tourniquet program focused on achieving best care for casualties with tourniquets. In 2006 that program was moribund but was soon reorganized. Tasks included finding used tourniquets about the hospital; cleaning, testing, maintaining, repairing, and drying them; storing them for future use; reordering to maintain adequate supplies; recording use for performance improvement; providing performance results to providers and trainers; providing feedback to manufacturers for design improvements; educating new providers; and coordinating among nurses and medics in operating rooms and the emergency department. The accomplishment of these tasks led directly to the successes illustrated in the publication of research, amendment of US Army first aid doctrine, improved casualty survival rates, and decreased incidence of what was once the most common cause of preventable death on the battlefield.<sup>2,3</sup>

Future research needs are many and include refined indications for specific populations with refinement of protocols and contraindications, refinements in training and

### Box 2

#### Summary of recent works

Tourniquet use before shock onset saves more lives than after shock; use them before extraction or transport.

Use scientifically designed, laboratory tested, and clinically validated tourniquets.

Use improvised windlass tourniquets only when well-designed tourniquets are unavailable.

Of tourniquets evaluated in care, the CAT is the best prehospital tourniquet, and the EMT is the best emergency department tourniquet.

Tourniquet education, training, and doctrine are vital and should be refined based on evidence.

The goal of emergency tourniquet use is to stop bleeding and stop the distal pulse.

Avoid tourniquet use over Hunter's canal near the knee because it risks ineffectiveness.

If one tourniquet is ineffective side-by-side use may better control hemorrhage.

Tourniquets work well proximal to the wound even on the forearm or leg and need not only be on the thigh or arm as sometimes recommended.

Clothing about a tourniquet should be removed at the first opportunity to avoid missed injuries and prevent loose placement.

Emergency tourniquets used to stop bleeding in foot and ankle casualties with major limb trauma improve survival rates, survival times, and permit easier resuscitation if the right device is used at the right time in the right way.

Limb salvage rates are high with modern damage control principles of resuscitation and vascular surgery.

Major limb trauma is more frequent now than earlier in the war and poses greater challenges for foot and ankle surgery and rehabilitation.

Limb function after emergency tourniquet use has not been associated with more impairment than like-injured casualties.

Current lessons learned from recent military experience and research are referents for civilian trauma care. Consideration is recommended for hemorrhage control in major limb trauma, the multiply injured casualty, or mass casualties.

doctrine, and full integration of use into damage control resuscitation practices (Box 2).

## LESSONS LEARNED ON TOURNIQUET USE FROM THE GLOBAL WAR ON TERROR

Tourniquets are powerful lifesaving devices and given scientific design, widespread training, modern doctrine, and thorough fielding to an integrated trauma system with rapid evacuation, have shown minor morbidity, but systems with inadequate devices, poor training, no doctrine, or slow evacuation have shown severe morbidity and mortality.<sup>50,51,60,61,71</sup> Tourniquets may save lives if the right device is used in the right way at the right time for the right patient.

## SUMMARY

Tourniquets are lifesaving in emergency care of bleeding casualties by controlling hemorrhage and preventing shock. Modern tourniquets used in combat after widespread fielding and universal training have been consistently associated with improved survival with minor morbidity.

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## REFERENCES

1. Beekley AC, Sebesta JA, Blackbourne LH, et al. Prehospital tourniquet use in Operation Iraqi Freedom: effect on hemorrhage control. *J Trauma* 2008;64(2): S28–37.
2. Kragh JF Jr, Walters TJ, Baer DG, et al. Practical use of emergency tourniquets to stop bleeding in major limb trauma. *J Trauma* 2008;64:S38–50.
3. Kragh JF Jr, Walters TJ, Baer DG, et al. Survival with emergency tourniquet use to stop bleeding in major limb trauma. *Ann Surg* 2009;249(1):1–7.
4. Pruitt BA Jr. The symbiosis of combat casualty care and civilian trauma care: 1914–2007. *J Trauma* 2008;64(Suppl 2):S4–8.
5. Dozier K. Breathing the fire: fighting to report-and survive-the war in Iraq. Des Moines (IA): Meredith Books; 2008.
6. Lakstein D, Blumenfeld A, Sokolov T, et al. Tourniquets for hemorrhage control on the battlefield: a 4-year accumulated experience. *J Trauma* 2003;54(Suppl 5): S221–5.
7. Brodie S, Hodgetts TJ, Ollerton J, et al. Tourniquet use in combat trauma: UK military experience. *J R Army Med Corps* 2007;153(4):310–3.
8. Anderson ID, Woodford M, Irving MH. Preventability of death from penetrating injury in England and Wales. *Injury* 1989;20(2):69–71.
9. Dorlac WC, DeBakey ME, Holcomb JB, et al. Mortality from isolated civilian penetrating extremity injury. *J Trauma* 2005;59(1):217–22.
10. Burns BD, Zuckerman S. Fragmentation panel of the static detonation committee, advisory council on Scientific Research and Technical Development. United Kingdom: Ministry of Supply; 1942. RC350.
11. Owens BD, Kragh JF Jr, Wenke JC, et al. Combat wounds in Operation Iraqi Freedom and Operation Enduring Freedom. *J Trauma* 2008;64(2):295–9.
12. Beebe G, DeBakey ME. Battle casualties: incidence, mortality and logistic considerations. Springfield (IL): Charles C Thomas; 1952. p. 77–147.

13. Owens BD, Kragh JF Jr, Macaitis J, et al. Characterization of extremity wounds in Operation Iraqi Freedom and Operation Enduring Freedom. *J Orthop Trauma* 2007;21(4):254–7.
14. Holmes RH. Wound ballistics and body armor. *JAMA* 1952;150(2):73–8.
15. Holmes RH, Enos WF Jr, Beyer JC. Medical aspects of body armor used in Korea. *JAMA* 1954;155(17):1477–8.
16. Ennis JL, Chung KK, Renz EM, et al. Joint Theater Trauma System implementation of burn resuscitation guidelines improves outcomes in severely burned military casualties. *J Trauma* 2008;64(Suppl 2):S146–51 [discussion: S151–2].
17. Holcomb JB, Wade CE, Michalek JE, et al. Increased plasma and platelet to red blood cell ratios improves outcome in 466 massively transfused civilian trauma patients. *Ann Surg* 2008;248(3):447–58.
18. Cordts PR, Brosch LA, Holcomb JB. Now and then: combat casualty care policies for Operation Iraqi Freedom and Operation Enduring Freedom compared with those of Vietnam. *J Trauma* 2008;64(Suppl 2):S14–20 [discussion: S20].
19. Fox CJ, Gillespie DL, Cox ED, et al. Damage control resuscitation for vascular surgery in a combat support hospital. *J Trauma* 2008;65(1):1–9.
20. Fox CJ, Gillespie DL, Cox ED, et al. The effectiveness of a damage control resuscitation strategy for vascular injury in a combat support hospital: results of a case control study. *J Trauma* 2008;64(Suppl 2):S99–106 [discussion: S106–7].
21. Bellamy RF. The causes of death in conventional land warfare: implications for combat casualty care research. *Mil Med* 1984;149(2):55–62.
22. Champion HR, Bellamy RF, Roberts CP, et al. A profile of combat injury. *J Trauma* 2003;54(Suppl 5):S13–9.
23. Acosta JA, Yang JC, Winchell RJ, et al. Lethal injuries and time to death in a level I trauma center. *J Am Coll Surg* 1998;186(5):528–33.
24. Sauaia A, Moore FA, Moore EE, et al. Epidemiology of trauma deaths: a reassessment. *J Trauma* 1985;38(2):185–93.
25. Holcomb JB, McMullin NR, Pearse L, et al. Causes of death in U.S. special operations forces in the Global War on Terrorism: 2001–2004. *Ann Surg* 2007;245(6):986–91.
26. Kelly JF, Ritenour AE, McLaughlin DF, et al. Injury severity and causes of death from Operation Iraqi Freedom and Operation Enduring Freedom: 2003–2004 versus 2006. *J Trauma* 2008;64(Suppl 2):S21–6 [discussion: S26–7].
27. Mabry RL, Holcomb JB, Baker AM, et al. United States Army Rangers in Somalia: an analysis of combat casualties on an urban battlefield. *J Trauma* 2000;49(3):515–28 [discussion: 528–9].
28. Mucciarone JJ, Llewellyn CH, Wightman JM. Tactical combat casualty care in the assault on Punta Paitilla Airfield. *Mil Med* 2006;171(8):687–90.
29. Grant RT, Reeve EB. Observations on the general effects of injury in man: with special reference to wound shock. Medical Research Council Special Report Series No. 277. London: HM Stationery Office; 1951. p. 3–67.
30. Beecher HK, Simeone FA, Burnett CH, et al. The internal state of the severely wounded man on entry to the most forward hospital. *Surgery* 1947;22:672–711.
31. Ebert RV, Stead EA. The effect of the application of tourniquets on the hemodynamics of the circulation. *J Clin Invest* 1940;19(4):561–7.
32. Emerson CP, Ebert RV. A study of shock in battle casualties: measurements of the blood volume changes occurring in response to therapy. *Ann Surg* 1945;122(5):745–72.
33. Dougherty PJ. Long-term follow-up study of bilateral above-the-knee amputees from the Vietnam War. *J Bone Joint Surg Am* 1999;81(10):1384–90.

34. Beecher HK. Early care of the seriously wounded man. *JAMA* 1951;145(4):193–200.
35. Feltis JM. Surgical experience in a combat zone. *Am J Surg* 1970;119:275–8.
36. Wilson WC. The wounded from Alamein: observations on wound shock and its treatment. *Army Medical Department Bulletin* 1943;(Suppl 7):1–32.
37. Artz CP, Howard JM, Sako Y, et al. Clinical experiences in the early management of the most severely injured battle casualties. *Ann Surg* 1955;141(3):285–96.
38. Rocko JM, Tischler C, Swan KG. Exsanguination in public: a preventable death. *J Trauma* 1982;22(7):635.
39. Swan KG, Swan RC. *Gunshot wounds: pathophysiology and management*. 2nd edition. Chicago: Yearbook; 1989. p. 226–7, 23–4.
40. National Research Council. *Burns, shock, wound healing and vascular injuries*. In: *Mil Surg Manuals*. Philadelphia: WB Saunders; 1943.
41. Klemcke HG, Baer DG, Pankratz VS, et al. Is survival time after hemorrhage a heritable, quantifiable trait? An initial assessment. *Shock* 2008;29(6):748–53.
42. Mannucci PM, Levi M. Prevention and treatment of major blood loss. *N Engl J Med* 2007;356(22):2301–11.
43. Tejwani NC, Immerman I, Achan P, et al. Tourniquet cuff pressure: the gulf between science and practice. *J Trauma* 2006;61(6):1415–8.
44. Klenerman L. *The tourniquet manual*. London: Springer; 2003.
45. NAEMT (National Association of Emergency Medical Technicians). *PHTLS prehospital trauma life support: military version*. 6th edition. St. Louis (MO): Mosby; 2007. p. 501–19.
46. Kalish J, Burke P, Feldman J, et al. The return of tourniquets: original research evaluates the effectiveness of prehospital tourniquets for civilian penetrating extremity injuries. *JEMS* 2008;33(8):44–54.
47. Swan KG Jr, Wright DS, Barbagioanni SS, et al. Tourniquets revisited. *J Trauma* 2009;66(3):672–5.
48. Cain JS. From the battlefield to our streets: how combat medicine is revolutionizing civilian prehospital care. *The War on Trauma Supplement*. *JEMS* 2008; Oct:16–23.
49. Walsh MJ, Walker G. *Seal!*. New York: Pocket Books; 1994. p.189.
50. Pillgram-Larsen J, Mellesmo S. [Not a tourniquet, but compressive dressing: experience from 68 traumatic amputations after injuries from mines] [English abstract]. *Tidsskr Nor Laegeforen* 1992;112(17):2188–90.
51. Pillgram-Larsen J. Compressive bandage, not tourniquet. Experience in 68 patients with traumatic amputation after mine injuries. *NATO Research & Technical Organisation Human Factors and Medicine Panel* 2004;109-02:1–8.
52. Ochoa J, Danta G, Fowler TJ, et al. Nature of the nerve lesion caused by a pneumatic tourniquet. *Nature* 1971;233(5317):265–6.
53. Graham B, Breault MJ, McEwen JA, et al. Perineural pressures under the pneumatic tourniquet in the upper extremity. *J Hand Surg Br* 1992;17(3):262–6.
54. Graham B, Breault MJ, McEwen JA, et al. Occlusion of arterial flow in the extremities at subsystolic pressures through the use of wide tourniquet cuffs. *Clin Orthop* 1993;286:257–61.
55. Walters TJ, Wenke JC, Kauvar DS, et al. Effectiveness of self-applied tourniquets in human volunteers. *Prehosp Emerg Care* 2005;9(4):416–22.
56. Wolf LH, Adkins TF. Tourniquet problems in war injuries. *Bull US Army Med Dep* 1945;87:77–84.
57. Walters TJ, Mabry RL. Issues related to the use of tourniquets on the battlefield. *Mil Med* 2005;170(9):770–5.

58. Walters TJ, Kragh JF, Baer DG. Influence of fiber-type composition on recovery from tourniquet-induced skeletal muscle ischemia-reperfusion injury. *Appl Physiol Nutr Metab* 2008;33(2):272–81.
59. Kragh JF Jr, Baer DG, Walters TJ. Extended (16-hour) tourniquet application after combat wounds: a case report and review of the current literature. *J Orthop Trauma* 2007;21(4):274–8.
60. Husum H, Ang SC, Fosse E. War surgery field manual. Penang (Malaysia): Third World Network; 1995. p. 85, 145.
61. Husum H, Gilbert M, Wisborg T, et al. Prehospital tourniquets: there should be no controversy. *J Trauma* 2004;56(1):214–5.
62. Moore FA. Tourniquets: another adjunct in damage control? *Ann Surg* 2009; 249(1):8–9.
63. Tien HC, Jung V, Rizoli SB, et al. An evaluation of tactical combat casualty care interventions in a combat environment. *J Am Coll Surg* 2008;207(2):174–8.
64. Wilson H, Roome NW. The effects of constriction and release of an extremity: an experimental study of the tourniquet. *Arch Surg* 1936;32:334–45.
65. van der Meer C, Valkenburg PW, Ariens AT, et al. Cause of death in tourniquet shock in rats. *Am J Physiol* 1966;210(3):513–25.
66. Miller DS. Vascular phenomena: vascular complications in orthopedics. *Instr Course Lect* 1948;5:48–58.
67. Middleton RW, Varian JP. Tourniquet paralysis. *Aust N Z J Surg* 1974;44(2):124–8.
68. Odinson A, Finsen V. Tourniquet use and its complications in Norway. *J Bone Joint Surg Br* 2006;88(8):1090–2.
69. McGraw RW, McEwen JA. The tourniquet. In: McFarlane RM, editor. *The hand and upper limb, unsatisfactory results in hand surgery*, vol. 3. New York: Churchill Livingstone; 1987. p. 5–13.
70. 75<sup>th</sup> Ranger Regiment Trauma Management Team. *Ranger Medic Handbook*. Las Vegas (NV): Cielo Azul Publications; 2007.
71. Böhler L. *The treatment of fractures*, vol.1. [Tretter H, Luchini HB, Kreuz F, et al, trans.] New York: Grune & Stratton; 1956. p. 126–8.