Extended (16-Hour) Tourniquet Application After Combat Wounds: A Case Report and Review of the Current Literature

John F. Kragh, Jr, MD, David G. Baer, PhD, and Thomas J. Walters, PhD

Summary: We present a case of emergency tourniquet use of unusually long duration. The patient was wounded during combat operations, and the subsequent battle and evacuation caused a significant delay in surgical treatment of his wounds. Emergency tourniquets can be lifesaving, but are not benign interventions. In general, the extent of tourniquet injury increases with increasing time of application. Despite having a tourniquet in place for 16 hours, the limb was salvaged and significant functional recovery was accomplished. We conducted a search of the published literature including the Medline database, and present a review of the relevant articles concerning emergency tourniquet use, tourniquet injury, and mitigating treatments. Given the widespread use of tourniquets in ongoing military operations, it seems likely that tourniquets will transition to civilian use. Thus it is important for physicians to understand tourniquet injury and appreciate that even extended tourniquet application times does not necessarily doom the affected limb.

Key Words: tourniquet, ischemia, reperfusion, gunshot wounds

(*J Orthop Trauma* 2007;21:274–278)

Approximately 50% of those who die from combat injury die from exsanguinating hemorrhage, the leading cause of death on the battlefield.[1] Based on World War II, Korean War, and Vietnam War data, Bellamy estimated 7% of exsanguination deaths resulted from limb wounds.[2] Similarly, in the current conflicts in Iraq and Afghanistan, about 2% of deaths have resulted from isolated extremity injuries (Col. John B. Holcomb, MD, unpublished data). Since the 17th century, medics and prehospital healthcare providers have used tourniquets to save the lives of patients with limb hemorrhage,[2–4] but little information exists on how long pre-hospital tourniquets can remain in place before complications like ischemia-reperfusion (I-R) injury become problematic. Surgeons performing elective orthopaedic surgery using pneumatic tourniquets adhere to clinical guidelines for regularly scheduled breathing times of reperfusion to permit longer surgeries within safe time limits of tourniquet duration, but such practices have substantial knowledge gaps as to degrees of risk to patients.[5] However, so-called safe tourniquet use in the operating room does not have the same meaning as so-called safe tourniquet use on the battlefield.[6] Tourniquets for elective orthopedic surgery are wider than battlefield tourniquets and are used to create bloodless operative fields, not to stop life-threatening hemorrhage. On the battlefield, considering circumstances such as continued gunfire, extended evacuation time, and limited capacity to monitor patients, the risk of tourniquet injury seldom outweighs the risk of removal and possible rebleeding and death on the battlefield. This case report and review of the literature explore the possibility that other factors in addition to tourniquet duration may play a part in the length of time a tourniquet can remain in place without limb loss.

CASE REPORT

During combat operations as part of Operation Anaconda (Afghanistan), a 37-year-old right-hand dominant male was piloting a CH-47 Chinook cargo helicopter when he was hit with a bullet of unknown caliber. The bullet penetrated the wrist and thumb resulting in profuse bleeding. The pilot rapidly landed the aircraft with the assistance of the co-pilot and quickly applied direct pressure to the wound, but was unable to control the bleeding. After landing, the aircraft and personnel on board continued to receive effective enemy fire, and the pilot was wounded in the left leg by a rocket-propelled grenade explosion and fragmentation. Thirty minutes after receiving the initial wound, the pilot applied a military tourniquet (a 50 mm wide strap with a spring clip) to his forearm. During the ongoing firefight with the enemy and 1 hour after injury, the tourniquet had not fully stopped wound bleeding. A special operations medic applied an improvised tourniquet composed of two cravats, a dowel, and a plastic cable tie to the forearm. The medic packed the wound with gauze and applied a field dressing. He did not remove the original tourniquet. These measures succeeded in stopping the bleeding. The medic administered intravenous fluids of unknown quantity and type to prevent shock. At 6 hours after injury, bleeding recurred from the wrist wound and a second medic tightened the tourniquet and

Accepted for publication January 27, 2007.

From the Bone and Soft Tissue Trauma Research Program, US Army Institute of Surgical Research; and the Department of Orthopaedics and Rehabilitation, Brooke Army Medical Center, Fort Sam Houston, TX.

No noninstitutional funding was received for the study. No competing interests or conflicts exist.

This manuscript does not contain information about medical devices.

Reprints: John F. Kragh, Jr, MD, Bone and Soft Tissue Trauma Research Program, US Army Institute of Surgical Research, 3400 Rawley E. Chambers Ave, Room 292-1, Building 3611, Fort Sam Houston, TX 78234-6315 (e-mail: john.kragh@amedd.army.mil).

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
01 APR 2007	**N/A**	**-**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Extended (16-hour) tourniquet application after combat wounds: a case report and review of the current literature	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
Kragh Jr. J. F., Baer D. G., Walters T. J.,	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
United States Army Institute of Surgical Research, JBSA Fort Sam Houston, TX 78234	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**5**	

was able to again stop the bleeding. During the ongoing firefight, both attending medics themselves were wounded and as a result of these wounds, continuing effective enemy fire, and the need to attend to other casualties, the medics were unable to continuously monitor the pilot's wound or provide additional treatment. The helicopter had landed at an elevation of 3000 m, where the air temperature was −15°C. The patient's hand and body were exposed to these environmental conditions for the first half day, during which time the patient laid prone in a 1 m deep snow drift. After the first half day, quilted soundproofing material was cut out of the aircraft and used as blankets to protect the soldiers from the wind and cold. Evacuation was delayed until 16 hours after injury due to ongoing combat, inclement weather, and mountainous terrain. Thus, the tourniquet was in place continuously for 16 hours and was not released until the patient was evacuated to a forward surgical team 17 hours after injury (Table 1).

On arrival at a forward surgical facility, the patient's condition was stable without shock or hypothermia. The wounds included significant radial-sided soft-tissue loss with exposed wrist joints and bones, loss of the first dorsal wrist compartment including the tendons, radial artery and veins, and radial sensory nerve (Fig. 1). With the severe soft-tissue loss, the radial artery was deemed irreparable. It is unknown to us if the ulnar artery was intact and providing collateral blood supply at the time of the evaluation at the forward surgical facility. Although compartment pressures were not measured, the patient had an established compartment syndrome as evidenced by pain on passive stretch. Initial surgical treatment included wound debridement and irrigation, radial artery ligation, three dorsal hand fasciotomies, and two palmar hand fasciotomies with obvious release of the tissue pressures. The orthopedic surgeon's postsurgical assessment was that hand preservation was questionable. The patient was subsequently evacuated from Afghanistan, a process that took 5 days. During this time dressing changes and wound care were periodically performed. Upon reaching the military evacuation hospital in Landstuhl, Germany, another operative debridement and irrigation was performed.

The patient was then transported to Walter Reed Army Medical Center, where he had repeated wound debridement and irrigation during the first month at this hospital. The radiographs at that time showed loss of the radial styloid, fractures at the base of the index and thumb metacarpal bones, and a scaphoid fracture with bone loss. The pronator quadratus appeared healthy and was used to cover the bony defect of the radial styloid. Soft tissues were advanced serially in these surgeries until delayed primary closure was achieved. No reconstruction of extrinsic thumb extensors was attempted. Due to a regional pain syndrome of the median nerve, a carpal tunnel release was done and symptoms resolved. Comprehensive and aggressive hand therapy relieved stiffness and pain. To improve wrist motion and articulation of the capitate in the lunate fossa, a proximal row carpectomy was done 7.5 months after injury. At 1 year after injury, the patient had prolonged weakness of the thumb muscles and hand intrinsic muscles that improved with therapy. To salvage the painful wrist, a wrist fusion was done at 1 year after injury.

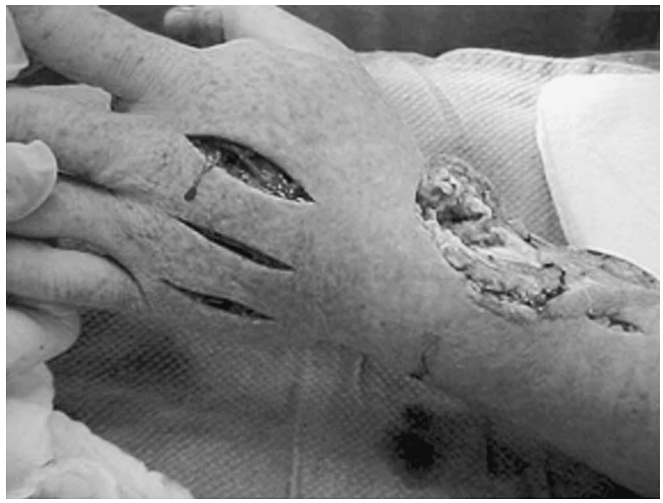

FIGURE 1. Photograph of left wrist gunshot wound at end of the initial surgery by the forward surgical team. Radial-sided tissue loss and dorsal fasciotomies are evident. No radiograph is available to reproduce photographically.

At 3 years after injury, the patient achieved near normal movement of the fingers, but the wrist had only 20 degrees of flexion and 10 degrees of extension. The patient achieved opposition of the thumb to the small finger, but motion remained less than the other hand as some stiffness persisted. The patient could only close the fist partially, but he used the hand for most activities of daily living. However, he was unable to support full bodyweight when pressing with the hand. Protective sensation on the dorsal hand was absent in the superficial radial nerve area and adjacent areas were hypersensitive. Left hand muscle testing of strength was 50% to 80% of the right dominant hand on workstation testing. Dexterity testing of both hands yielded nearly equal results. The patient's hand function was sufficient to allow him to return to flight duties, including piloting helicopters. We have no final function photographs or radiographs.

TABLE 1. Significant Events and Results

Date	Event	Result
March 4, 2002	Gunshot wound	Right forearm and thumb partially avulsed, profuse bleeding
March 5, 2002	Surgical debridement	Fasciotomies. Dorsal hand compartments were released
March 10, 2002	Repeat debridement	Wounds clean
October 23, 2002	Proximal row carpectomy	Residual pain
February 2003	Wrist fusion	Pain resolved
May 2004	Return to flight duties	Functioning well
March 2005	Latest follow up	

DISCUSSION

The main finding of this case report is that a battlefield tourniquet can be used successfully for a prolonged time despite the fact that the risk of complications is generally higher as duration of use increases. Tourniquet use for 1 to 3 hours during surgical procedures is commonplace and carries a very low risk of complications.[5,7,8] However, it is generally thought that skeletal muscle cannot tolerate ischemia for more than 6 hours without complete loss of viability.[8] It is therefore notable that in the present case, limb salvage was successful after more than 16 hours of tourniquet-induced ischemia. Explanations of this apparent contradiction include the distal injury, cooling of the extremity during tourniquet application,[9–11] and appropriate fasciotomies to resolve compartment syndrome. Additionally, a short period of reperfusion may

have occurred at 6 hours after injury as evidenced by resumed bleeding, and this may have affected eventual outcome.

The emergency tourniquets were placed at the mid-forearm, limiting ischemia to the skin, nerves, tendons, and muscles of the hand and wrist. Although skin and tendon are relatively insensitive to ischemia, both muscle and nerve are susceptible to I-R injuries.[12] In this case, except for weakness due to lost tendons from wounding, the muscle injury evident by the prolonged weakness appears to be mainly from tourniquet injury. Prolonged tourniquet times adversely affect muscle contractile function and this is thought to be due to myocyte changes after I-R.[13] The transient regional pain syndrome several weeks after wounding may have been related to the traumatic injury, tourniquet-induced nerve injury, or other treatments. The wrist stiffness appeared to be from the wrist fusion that relieved pain with motion and the resultant surgical stiffness was expected with the fusion. Prolonged tourniquet application is associated with a high risk of compartment syndrome.[8,13] Fasciotomies are done routinely for high-energy war wounds by the forward surgeons when there is limited monitoring and surgical capacity during long aeromedical flights and transportation between hospitals.[14] Fasciotomies likely contributed to successful tissue salvage in the present case (Fig. 1). In addition to appropriate surgical care, ambient cooling of the limb may have mitigated some of the expected adverse effects of extended tourniquet time. Cooler limbs tolerate longer ischemia durations.[9–11] The first tourniquet's ineffectiveness and the need to retighten the second may mean that the effective cool ischemia time for the limb in this report may have been less than 16 hours. When early triage and transport cannot be affected, use of tourniquets while under combat fire is a practical option for the patient and his medic.

Tourniquets have been used for hemorrhage control on the battlefield for over 300 years.[4] The recommendations for their use have swung back and forth like a pendulum between the pros and cons.[3,15,16] In peacetime, tourniquets are generally shunned by hospital-based surgeons, whereas in wartime tourniquets tend to be advocated by forward emergency personnel.[3,17] Analysis of data from Vietnam[2] and from the Battle of Mogadishu[18] revealed that 7% to 10% of soldiers killed in action died from exsanguinating extremity injuries amenable to tourniquet application. This caused military medical leaders to reconsider the balance between potential lifesaving benefits and fear of related complications.[6,16,19,20] Current recommendations dictate the use of tourniquets to stop severe extremity bleeding while under fire.[21] Further changes in tourniquet use doctrine are related to a dramatic increase in the availability of effective tourniquets. As a result of laboratory and field testing in human volunteers,[20] effective, lightweight, easy-to-use tourniquets have been identified and fielded to all deploying soldiers, Marines, and special forces. Feedback from deployed surgeons (including one of us, J.F.K.) indicates that these devices are indeed lifesaving.

Tourniquet-related complications involve a number of mechanisms. Compression and shear of tissues under the tourniquet can result in nerve palsies[3,13,22–24] and skin injury.[13,25] I-R injuries to tissues beneath and distal to the tourniquet causes inflammation[8,26] and oxidative and nitrosative stress[27] leading to muscle necrosis with resultant loss of function.[7,8,28] Microvascular injury leads to edema that in turn can contribute to the development of acute compartment syndrome,[29,30] although in extremity trauma patients it is difficult to differentiate between the contribution of I/R and direct trauma. Compartment syndromes occur at lower compartmental pressures with declining blood pressure,[31] potentially placing the patient who has hypovolemic hypotension at greater risk. Overresuscitation in trauma patients can result in compartment syndrome in uninjured limbs[32–34] and may be exacerbated when combined with tourniquet application due to additive effects. In very rare cases, patients have been reported to developed rhabdomyolysis and acute renal failure after surgical tourniquet application.[35,36]

Much work has been done to minimize under tourniquet injury. Research has demonstrated that there is an inverse relationship between the tourniquet pressure required to occlude arterial flow and the circumference of the limb.[37–40] Additionally, there is also an inverse relationship between tourniquet width and the pressure required to occlude arterial flow.[38–40] These considerations have been taken into account in design and use guidelines for pneumatic surgical tourniquets. On the battlefield the need for a rugged, lightweight tourniquet that can be used for a wide range of limb sizes and wound locations precludes use of wide pneumatic devices. There is no research to date on the incidence of compression injury with the improvised (cravat and stick) or strap-type tourniquets. There are several practical ways to minimize injury when prehospital emergency tourniquets are used. These include limiting tourniquet time by expediting evacuation or conversion to other hemostatic methods when possible, and limiting compression injury by tightening the tourniquet only to the extent necessary to stop bleeding.[21]

The magnitude of I-R injury is related to the duration of tourniquet use.[5,7,8,13] This can be greatly modified by tissue temperature.[9–11] Limb cooling during ischemia offers protection by reducing metabolic demand[41] and inhibition of microvascular and endothelial dysfunction.[42] Clinically[43–45] and experimentally[46–48] the use of limb cooling during ischemia has shown significant benefit. These studies typically involve a reduction in deep-tissue temperature of 5°C to 10°C; however, it has been demonstrated that even a 2°C to 4°C reduction in muscle temperature can have a beneficial effect.[46,49] During the US Army experience in the Italian campaign of World War II, Wolf et al credited the winter temperatures for toleration of tourniquet use for up to 8 hours "without apparent deleterious effect."[50] Reports exist for successful replantation of severed limbs and digits with up to 94 hours of cool ischemia time.[51,52] The magnitude of ischemic injury is a direct function of the tissue temperature down to 10°C[41]; however, there is a limit to beneficial hypothermia, as temperatures less than 5°C have been shown to increase muscle injury.[53] In contrast to the ischemic period, the beneficial effects of hypothermia during reperfusion are equivocal.[54–56] Increasing tissue temperature has the opposite effect from decreasing it, and even subtle increases can be extremely deleterious.[11,57,58]

The practice of intermittent reperfusion is common in surgical practice and can significantly extend the duration of

safe tourniquet application. However, in battlefield applications there is generally no ability to limit hemorrhage during intermittent reperfusion, and no ability to administer blood products to replace lost volume. History has shown the practice to be ill advised, resulting in many deaths due to incremental exsanguination[50] and current use guidelines expressly forbid the practice.[21]

Although intermittent reperfusion in the battlefield setting is unwise, tourniquets are not definitive hemorrhage control devices due to the issues of I-R discussed above as well as crush injury beneath the tourniquet and the pain caused by their use. Emergency tourniquet use as an adjunct or even first measure to stop bleeding is a damage control tool that can be lifesaving, but they are powerful devices whose application requires knowledge and skill to optimally serve patients. Patient tolerance of tourniquet use has been studied[59,60] and may be problematic in prolonged use as longer durations can be intolerable in alert patients.[13] When tourniquets are used for emergency hemorrhage control, efforts should be made to transition to less injurious forms of hemorrhage control.[6] Improved emergency hemostatic measures recently researched and developed have included: pressure dressings,[61] fibrin dressings and foams,[62,63] dressings,[64] zeolite dressings,[65] glucosamine dressings,[66] and injectable recombinant human factor VII.[62,63,67–70] These new products come in different shapes, sizes, and materials and may work differently in wounds of various shapes, sizes, and tissues. In addition, concern for tourniquet-induced crush injury leads to the recommendation that strap-type tourniquets be transitioned to less painful pneumatic tourniquets as soon as practical. Ongoing research on pharmaceutical agents to limit I-R may be applicable in reducing the sequela associated with tourniquet use by limiting the pathophysiology of I-R to the muscle, skin, nerve, and vasculature.

Abrasions, blisters, and other under tourniquet injuries can be prevented by use of underwraps[25,71] and I-R may be attenuated by limb cooling with aims to avoid cold injury.[72,73] Medication or pretreatments may attenuate I-R, but which medications are indicated for what purposes are yet to be determined.[13] Tourniquet misuse can cause more bleeding[74] through exsanguination of distally disrupted veins or expanding hematomas if veins are occluded under the tourniquet but arterial flow is not stopped.[13] Nonetheless, the use of tourniquets to stop limb exsanguination may be a first measure for a provider under gunfire, in tactical darkness, or a mass casualty situation.[15,16,21]

CONCLUSIONS

Tourniquets stop bleeding and save lives but sometimes at the cost of limbs. The case described here was a particularly fortunate one; after 16 hours of continuous tourniquet application, not only was the life of the pilot saved, but the limb was salvaged. This is due to the combination of skilled medics, reduced temperatures, accomplished orthopedic surgeons at the forward surgical facility, evacuation hospital, and (in the United States) extensive rehabilitation therapy. The combination of these critical factors suggests that we can reduce the risk of limb loss even when tactical constraints cause tourniquet application times to be extended by improving tourniquet design, user training, and limb cooling. Under optimal circumstances limbs may be preserved despite prolonged tourniquet time necessitated by inability to evacuate the patient. This scenario may mirror the rare case in civilian medicine where remote location or entrapment of the patient prevents timely delivery of definitive care.

ACKNOWLEDGMENTS

The authors thank George Peoples, Tad L. Gerlinger, Cory Lamoreaux, John Schwegmann, Gerald L. Farber, Steven Rose, and Lisa Smurr for data and Amy W. Newland, Charles E. Wade, PhD, and John B. Holcolmb, MD for manuscript review.

REFERENCES

1. Champion HR, Bellamy RF, Roberts CP, et al. A profile of combat injury. *J Trauma*. 2003;54:S13–S19.
2. Bellamy RF. The causes of death in conventional land warfare: implications for combat casualty care research. *Mil Med*. 1984;149:55–62.
3. Lakstein D, Blumenfeld A, Sokolov T, et al. Tourniquets for hemorrhage control on the battlefield: a 4 year accumulated experience. *J Trauma*. 2003;54:S221–S225.
4. Mabry RL. Tourniquet use on the battlefield. *Mil Med*. 2006;171: 352–356.
5. Klenerman L. Tourniquet time—how long? *Hand*. 1980;12:231–234.
6. Walters TJ, Mabry RL. Issues related to the use of tourniquets on the battlefield. *Mil Med*. 2005;170:770–775.
7. Kam PC, Kavanagh R, Yoong FF, et al. The arterial tourniquet: pathophysiological consequences and anaesthetic implications. *Anaesthesia*. 2001;56:534–545.
8. Blaisdell FW. The pathophysiology of skeletal muscle ischemia and the reperfusion syndrome: a review. *Cardiovasc Surg*. 2002;10:620–630.
9. Allen FM. Resistance of peripheral tissues to asphyxia at various temperatures. *Surg Gynecol Obstet*. 1938;67:746–751.
10. Flatt AE. Tourniquet time in hand surgery. *Arch Surg*. 1972;104:190–192.
11. Bruner JM. Safety factors in the use of the pneumatic tourniquet for heomostasis in surgery of the hand. *J Bone Joint Surg Am*. 1951;33: 221–224.
12. Korthals JK, Maki T, Gieron MA. Nerve and muscle vulnerability to ischemia. *J Neurol Sci*. 1985;71:283–290.
13. Klenerman L. *The Tourniquet Manual: Principles and Practice*. New York: Springer; 2003.
14. West BC, Bentley R, Place RJ. In-flight transfusion of packed red blood cells on a combat search and rescue mission: a case report from operation enduring freedom. *Mil Med*. 2004;169:181–183.
15. Borden Institute (US). *Emergency War Surgery.* 3rd ed. Washington DC: Office of the Surgeon General, US Army, Borden Institute, Walter Reed Army Medical Center; 2004.
16. Butler FK Jr, Hagmann J, Butler EG. Tactical combat casualty care in special operations. *Mil Med*. 1996;161(Suppl):3–16.
17. US Department of Defense. *Emergency War Surgery.* 1st rev. Washington DC: US Government Printing Office; 1975.
18. 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;49:515–528.
19. Calkins D, Snow C, Costello M, et al. Evaluation of possible battlefield tourniquet systems for the far-forward setting. *Mil Med*. 2000;165: 379–384.
20. Walters TJ, Wenke JC, Kauvar DS, et al. Effectiveness of self-applied tourniquets in human volunteers. *Prehosp Emerg Care*. 2005;9:416–422.
21. *PHTLS: Basic and Advanced Prehospital Trauma Life Support; Military Edition*. 5th ed. St. Louis: Elsevier Mosby; 2005.
22. Volpin G, Said R, Simri W, et al. [Nerve palsies in a soldier with penetrating injuries following prolonged use of limb tourniquets]. *Harefuah*. 1999;136:352–355.
23. Middleton RW, Varian JP. Tourniquet paralysis. *Aust N Z J Surg*. 1974;44: 124–128.

24. Odinsson A, Finsen V. The position of the tourniquet on the upper limb. *J Bone Joint Surg Br*. 2002;84:202–204.
25. Din R, Geddes T. Skin protection beneath the tourniquet. A prospective randomized trial. *ANZ J Surg*. 2004;74:721–722.
26. Gute DC, Ishida T, Yarimizu K, et al. Inflammatory responses to ischemia and reperfusion in skeletal muscle. *Mol Cell Biochem*. 1998;179:169–187.
27. Rubin BB, Romaschin A, Walker PM, et al. Mechanisms of postischemic injury in skeletal muscle: intervention strategies. *J Appl Physiol*. 1996;80: 369–387.
28. Jacobson MD, Pedowitz RA, Oyama BK, et al. Muscle functional deficits after tourniquet ischemia. *Am J Sports Med*. 1994;22:372–377.
29. Odinsson A, Finsen V. Tourniquet use and its complications in Norway. *J Bone Joint Surg Br*. 2006;88:1090–1092.
30. Wakai A, Winter DC, Street JT, et al. Pneumatic tourniquets in extremity surgery. *J Am Acad Orthop Surg*. 2001;9:345–351.
31. Heppenstall RB, Sapega AA, Izant T, et al. Compartment syndrome: a quantitative study of high-energy phosphorus compounds using 31P-magnetic resonance spectroscopy. *J Trauma*. 1989;29:1113–1119.
32. Ablove RH, Babikian G, Moy OJ, et al. Elevation in compartment pressure following hypovolemic shock and fluid resuscitation: a canine model. *Orthopedics*. 2006;29:443–445.
33. Block EF, Dobo S, Kirton OC. Compartment syndrome in the critically injured following massive resuscitation: case reports. *J Trauma*. 1995;39: 787–791.
34. Tremblay LN, Feliciano DV, Rozycki GS. Secondary extremity compartment syndrome. *J Trauma*. 2002;53:833–837.
35. Palmer SH, Graham G. Tourniquet-induced rhabdomyolysis after total knee replacement. *Ann R Coll Surg Engl*. 1994;76:416–417.
36. Williams JE Jr, Tucker DB, Read JM 3rd. Rhabdomyolysis-myoglobinuria: Consequences of prolonged tourniquet. *J Foot Surg*. 1983;22:52–56.
37. Shaw JA, Murray DG. The relationship between tourniquet pressure and underlying soft-tissue pressure in the thigh. *J Bone Joint Surg Am*. 1982; 64:1148–1152.
38. Moore MR, Garfin SR, Hargens AR. Wide tourniquets eliminate blood flow at low inflation pressures. *J Hand Surg [Am]*. 1987;12:1006–1011.
39. Crenshaw AG, Hargens AR, Gershuni DH, et al. Wide tourniquet cuffs more effective at lower inflation pressures. *Acta Orthop Scand*. 1988;59: 447–451.
40. 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;286:257–261.
41. Sapega AA, Heppenstall RB, Sokolow DP, et al. The bioenergetics of preservation of limbs before replantation. The rationale for intermediate hypothermia. *J Bone Joint Surg Am*. 1988;70:1500–1513.
42. Schaser KD, Stover JF, Melcher I, et al. Local cooling restores microcirculatory hemodynamics after closed soft-tissue trauma in rats. *J Trauma*. 2006;61:642–649.
43. An H, Jiang D, Ni W. [Experimental study prevention of reperfusion injury of skeletal muscle by local hypothermia and its clinical application]. *Zhongguo Xiu Fu Chong Jian Wai Ke Za Zhi*. 1997;11:52–55.
44. Swanson AB, Livengood LC, Sattel AB. Local hypothermia to prolong safe tourniquet time. *Clin Orthop*. 1991;264:200–208.
45. Ikemoto Y, Kobayashi H, Usui M, et al. Changes in serum myoglobin levels caused by tourniquet ischemia under normothermic and hypothermic conditions. *Clin Orthop*. 1988;234:296–302.
46. Skjeldal S, Grogaard B, Nordsletten L, et al. Protective effect of low-grade hypothermia in experimental skeletal muscle ischemia. *Eur Surg Res*. 1992;24:197–203.
47. Awerbuck D, Luong V, Plyley MJ, et al. Skeletal muscle form and function after 4 hr ischemia-hypothermia. *J Surg Res*. 1994;57:480–486.
48. Fish JS, McKee NH, Kuzon WM Jr, et al. The effect of hypothermia on changes in isometric contractile function in skeletal muscle after tourniquet ischemia. *J Hand Surg [Am]*. 1993;18:210–217.
49. Skjeldal S, Torvik A, Nordsletten L, et al. Local hypothermia during ischemia or reperfusion in skeletal muscles. *Res Exp Med (Berl)*. 1993; 193:73–80.
50. Wolff LH, Adkins TF. Tourniquet Problems in War Injuries. *The Bulletin of the U.S. Army Medical Department*. 1945;37:77–84.
51. Wei FC, Chang YL, Chen HC, et al. Three successful digital replantations in a patient after 84, 86, and 94 hours of cold ischemia time. *Plast Reconstr Surg*. 1988;82:346–350.
52. VanderWilde RS, Wood MB, Zu ZG. Hand replantation after 54 hours of cold ischemia: a case report. *J Hand Surg [Am]*. 1992;17:217–220.
53. Wright CJ. Effect of femoral profundaplasty on blood flow. *Can J Surg*. 1983;26:325–327.
54. Skjeldal S, Nordsletten L, Kirkeby OJ, et al. Perfusion in the anterior tibial muscle measured by laser Doppler flowmetry after graded periods of hindlimb ischemia in rats. *Int J Microcirc Clin Exp*. 1993;12: 107–118.
55. Wright JG, Araki CT, Belkin M, et al. Postischemic hypothermia diminishes skeletal muscle reperfusion edema. *J Surg Res*. 1989;47: 389–396.
56. Gurke L, Marx A, Sutter PM, et al. Function of fast- and slow-twitch rat skeletal muscle following ischemia and reperfusion at different intramuscular temperatures. *Eur Surg Res*. 2000;32:135–141.
57. Petrasek PF, Homer-Vanniasinkam S, Walker PM. Determinants of ischemic injury to skeletal muscle. *J Vasc Surg*. 1994;19:623–631.
58. Bruner JM. Time, pressure, and temperature factors in the safe use of the tourniquet. *Hand*. 1970;2:39–42.
59. Hutchinson DT, McClinton MA. Upper arm and forearm tourniquet tolerance. *J Hand Surg [Br]*. 1994;19:672.
60. Maury AC, Roy WS. A prospective, randomized, controlled trial of forearm versus upper arm tourniquet tolerance. *J Hand Surg [Br]*. 2002; 27:359–360.
61. Naimer SA, Chemla F. Elastic adhesive dressing treatment of bleeding wounds in trauma victims. *Am J Emerg Med*. 2000;18:816–819.
62. Holcomb JB. Methods for improved hemorrhage control. *Crit Care*. 2004; 8:S57–S60.
63. Kheirabadi BS, Acheson EM, Deguzman R, et al. Hemostatic efficacy of two advanced dressings in an aortic hemorrhage model in Swine. *J Trauma*. 2005;59:25–34.
64. Wedmore I, McManus JG, Pusateri AE, et al. A special report on the chitosan-based hemostatic dressing: experience in current combat operations. *J Trauma*. 2006;60:655–658.
65. Alam HB, Chen Z, Jaskille A, et al. Application of a zeolite hemostatic agent achieves 100% survival in a lethal model of complex groin injury in Swine. *J Trauma*. 2004;56:974–983.
66. Vournakis JN, Demcheva M, Whitson AB, et al. The RDH bandage: hemostasis and survival in a lethal aortotomy hemorrhage model. *J Surg Res*. 2003;113:1–5.
67. Dutton RP, Hess JR, Scalea TM. Recombinant factor VIIa for control of hemorrhage: early experience in critically ill trauma patients. *J Clin Anesth*. 2003;15:184–188.
68. Harrison TD, Laskosky J, Jazaeri O, et al."Low-dose" recombinant activated factor VII results in less blood and blood product use in traumatic hemorrhage. *J Trauma*. 2005;59:150–154.
69. Martinowitz U, Michaelson M. Guidelines for the use of recombinant activated factor VII (rFVIIa) in uncontrolled bleeding: a report by the Israeli Multidisciplinary rFVIIa Task Force. *J Thromb Haemost*. 2005;3: 640–648.
70. Martinowitz U, Zaarur M, Yaron BL, et al. Treating traumatic bleeding in a combat setting: possible role of recombinant activated factor VII. *Mil Med*. 2004;169(Suppl 12):16–18.
71. De Souza BA. Avoiding tourniquet complications: a simple idea. *Plast Reconstr Surg*. 2003;111:1574–1575.
72. Melamed E, Glassberg E. [Non-freezing cold injury in soldiers]. *Harefuah*. 2002;141:1050–1054.
73. Moran DS, Heled Y, Shani Y, et al. Hypothermia and local cold injuries in combat and non-combat situations–the Israeli experience. *Aviat Space Environ Med*. 2003;74:281–284.
74. Bunker TD, Ratliff AH. Uncontrollable bleeding under tourniquet. *Br Med J (Clin Res Ed)*. 1984;288:1905.