Role of the Windlass in Improvised Tourniquet Use on a Manikin Hemorrhage Model

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ABSTRACT

Background: In emergencies when commercially designed tourniquets are unavailable, hemorrhage may need to be controlled with improvised tourniquets. In the aftermath of the Boston Marathon bombing, no improvised strap-and-windlass tourniquets were used to treat casualties; tourniquets without windlasses were used. The purpose of the present study is to determine the effectiveness of improvised tourniquets with and without a windlass to better understand the role of the windlass in tightening the tourniquet strap. **Methods:** An experiment was designed to test the effectiveness of improvised strap-and-windlass tourniquets fashioned out of a tee shirt on a manikin thigh. Two users conducted 40 tests each with and without the use of a windlass. **Results:** Without a windlass, improvised tourniquets failed to stop bleeding in 99% of tests (79 of 80 tests). With a windlass, improvised tourniquets failed to stop bleeding in 32% of tests ($p < .0001$). In tests with no windlass, attempts to stop the pulse completely failed (100%, 80 of 80 tests). With a windlass, however, attempts to stop the pulse failed 31% of the time (25 of 80 tests); the difference in proportions was significant ($p < .0001$). **Conclusions:** Improvised strap-and-windlass tourniquets were more effective than those with no windlass, as a windlass allowed the user to gain mechanical advantage. However, improvised strap-and-windlass tourniquets failed to control hemorrhage in 32% of tests.

KEYWORDS: *first aid; hemorrhage; tourniquets; shock; damage control; tourniquet, makeshift; tourniquet, homemade; strap-and-windlass*

Introduction

Explosions on Boylston Street near the crowded finish line of the 2013 Boston Marathon caused more than 260 casualties, which, in turn, spurred nearby people to improvise tourniquets to stop limb bleeding.[1,2] These first people to respond made tourniquets fashioned out of clothing such as shirts from nearby runners or from blast-damaged storefronts, for use on casualties who were at risk of death by wound exsanguination.[2,3] No longer bystanders, these responders gave first aid by wrapping and tightening a shirt around a limb, and these makeshift tourniquets reportedly helped save lives.[4] Such field tourniquets were replaced at the hospitals with dressings, commercial tourniquets, or blood pressure cuffs[2,3]; observers noted that tourniquets improvised by first responders were ineffective, as hemorrhage was not controlled.[1,2] The lifesaving–ineffective contradiction indicates confusion and a need to better understand improvised tourniquets. The confusion and contradiction exist fundamentally because there is essentially no substantial research into the optimal use of improvised tourniquets. This lack of research leaves knowledge gaps unfilled regarding best tourniquet practices.

A strap-and-windlass design is an ancient way to use a rod to wind a strap more tightly around a limb; a key step in improvising tourniquets is to twist a strap with a windlass to gain mechanical advantage in tightening. However, to our knowledge, no one in Boston reported windlass use with an improvised tourniquet. If the role of the windlass was made clear, then tourniquet practice might be improved. A theory is that an inadequately tightened strap can occlude limb veins but not arteries; venous tourniquets control venous bleeding while arterial tourniquets control both venous and arterial bleeding. If so, then a venous tourniquet may be effective only for venous bleeding and not for arterial bleeding.[5] Furthermore, such effectiveness for venous hemorrhage may be only brief since paradoxical bleeding may soon occur.[5]

The purpose of the present study is to determine the effectiveness of improvised tourniquets with and without a windlass to better understand the role of the windlass in gaining mechanical advantage in tightening the tourniquet strap.

Methods

This study was conducted under a protocol reviewed and approved by the Regulatory Compliance Division

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of the US Army Institute of Surgical Research. A laboratory experiment was designed to compare the function of improvised tourniquets with and without windlass use. The study design was based on first responder actions in Boston.

The study group was a set of tests of an improvised tourniquet design with a windlass. The strap-and-windlass design included a strap that was a cotton tee shirt; the shirt was used for each test. For this experiment, a set of standard bamboo chopsticks was used as the windlass mechanism; we used six chopsticks taped together into a functionally single windlass. The windlass reliably kept itself in a bundle. The windlass, after insertion into the tourniquet knot, was twisted by the user in 180° turns, thereby tightening the tourniquet strap. The control group was constituted similarly to the study group except there was no windlass used.

There were two tourniquet users—one experienced and one inexperienced in tourniquet use. The experienced user always preceded the inexperienced user, and the control group was tested by each user before the study group was tested. There were 40 tests per group per user; hence, each user had 80 tests (40 tests times two groups times two users), or 160 tests altogether for the experiment.

A black tee shirt (lightly worn, cotton, short sleeve, large men's size; Lands End, Inc.; www.landsend.com) was used in the trials. The shirt was folded into a strap to encircle the limb. The line of folding was diagonal from one sleeve to the opposite waist to maximize circumferential length around the thigh. Users wrapped the shirt around the manikin at the proximal thigh, tying a half-knot and pulling tightly to maintain tension in the strap and create pressure on the underlying skin. The user terminated the test when one of three conditions existed: (1) hemorrhage was controlled; (2) there was futility after repeated efforts to generate sufficient tension (repeated efforts led only to unceasing failure); or (3) when unsafe use occurred (e.g., lacerated skin of the manikin).

When a windlass was tested, the same procedure was used, except the user put the windlass atop the half-knot and then tied another half-knot atop the windlass before twisting it to wind the knot and supposedly create more strap tension.

The tourniquets were tested on a manikin in the laboratory. The investigators used a HapMed™ Leg Tourniquet Trainer (CHI Systems Inc.; www.chisystems.com/index.php)—a simulated right-thigh (leg number 000F) with an above-knee amputation injury was the testing apparatus.[6, 7] The medial hip had an embedded computer that included a smartphone-like touchpad. Software (version 1.9, CHI Systems Inc.; www.chisystems.com/index.php) integral to the thigh allowed the manikin to stand alone and be operated by user input through finger touch on the pad. The thigh had no blood, but bleeding was represented by red lights that transilluminated the wound. The number of lights illuminated represented the rate of bleeding—all 26 lights on meant maximal bleeding; no lights on meant bleeding had stopped. Users tightened tourniquets until they perceived that simulated bleeding stopped or until efforts proved futile. Arterial pulses were palpable in the popliteal artery area behind the knee. The time for hemorrhage control was that interval from iteration initiation until cessation of bleeding, as evidenced by the absence of lights. Effectiveness was defined as cessation of blood loss. When hemostasis was achieved, users stopped turning the windlasses. The manikin settings included a constant hemorrhage rate (635mL/min); the resulting bleed-out time in this scenario was 4 minutes—240 seconds in which to successfully apply the tourniquet. The system reported blood loss volume as calculated from the product of hemorrhage rate and time until hemorrhage control. The casualty had a medium build and the setting was Care Under Fire, a setting resembling emergency care when under gunfire.

The critical outcome was effectiveness (hemorrhage controlled: yes or no). An important outcome was absence of palpable pulse distal to the tourniquet (yes or no). Minor outcomes included time to cessation of bleeding (seconds), pressure applied to the skin by the tourniquet (mmHg), and the volume of blood loss (mL). Effectiveness, time to stop bleeding, and pressure were measured by the manikin, while pulse stoppage was measured by the user. Historically, a threshold has been used as a rough guide to tourniquet effectiveness such that when 80% or more of uses are successfully effective, then the tourniquet has reached a minimal level of reliability—a so-called 80% solution.[8] Descriptive statistics were used to analyze results. For categorical variables, a chi-squared test was used and the likelihood ratio p values were reported (SAS Institute Inc.; www.sas.com). For continuous variables, a mixed model was used with user as a random effect, as there was a clear user difference in the results.[8] Confidence limits were adjusted Wald 95% confidence intervals (CIs). Significance for results was established when p values were less than .05.

Results

The Role of the Windlass in Improvised Strap-and-Windlass Tourniquet Use

Without a windlass, improvised tourniquets failed to stop bleeding 79 times out of 80 tests (99%; 95% CI, 93%–100%) (Table 1). With a windlass, improvised tourniquets failed to stop bleeding 26 times out of 80 tests (32%; 95% CI, 23%–43%) (Table 1). The difference in proportions, 99% versus 32%, was statistically significant ($p < .0001$). However, neither group was reliably effective: Both with and without a windlass, improvised tourniquets did not achieve 80% effectiveness, the minimum threshold of reliable effectiveness.

Table 1 *Hemorrhage Control Results by Windlass or No Windlass*

Windlass Used	Failed Hemorrhage Control		Total Tests, No.
	Tests, No. (%)	Adjusted Wald 95% CI	
No	79 (99)	93%–100%	80
Yes	26 (32)	23%–43%	80

Note: CI, confidence interval.

Pulse results were nearly the same as the hemorrhage control results in that the windlass played a major role in improvised tourniquet performance (Table 2). In tests with no windlass, attempts to stop the pulse failed every time (80 of 80 tests, 100%; 95% CI, 96%–100%). With a windlass, however, attempts to stop the pulse failed 31% (95% CI, 22%–42%) of the time (25 of 80 tests); the difference in proportions was significant ($p < .0001$). The similarity between results of pulse stoppage and hemorrhage control indicated that the two phenomena were closely related.

Time to Bleeding Cessation, Pressure, and Blood-Loss Volume Results

The mean time to bleeding cessation with no windlass was 59 seconds (95% CI, 54–64 seconds), and all but one test with no windlass ended in failure (79 of 80 tests; 95% CI, 93%–100%). On the other hand, the mean time to bleeding cessation with a windlass was 98 seconds (95% CI, 90–105 seconds), and 32% (26 of 80 tests; 95% CI, 23%–43%) of tests ended in failure. The difference in mean times was significant ($p < .0001$; 95% CI for difference, 28–48).

Table 2 *Pulse Stoppage Results by Windlass or No Windlass*

Windlass Used	Failed Pulse Cessation		Total Tests, No.
	Tests, No. (%)	Adjusted Wald 95% CI	
No	80 (100)	96%–100%	80
Yes	25 (31)	22%–42%	80
Total	105		160

Note: CI, confidence interval.

The mean pressure applied with no windlass was 46mmHg (95% CI, 35mmHg–58mmHg), whereas with a windlass, it was 114mmHg (95% CI, 92mmHg–136mmHg; $p < 0.0001$; 95% CI for difference, 42mmHg–92mmHg). Windlass use increased the pressure under the tourniquet compared to no windlass use.

The mean blood loss volume with no windlass was 415mL (95% CI, 383mL–446mL) and with a windlass was it was 648mL (95% CI, 596mL–700mL; $p < .0001$; 95% CI for difference, 172mL–294mL). When blood loss was measured as volume per time, the windlass tests bled at an average of 6.7mL/s (95% CI, 6.5mL/s–6.9mL/s) until bleeding was stopped, while the tests without a windlass bled at an average of 7.1mL/s (95% CI, 6.9mL/s–7.3mL/s) throughout the test period.

The Role of the User

There were interesting results that varied by user. Even with the user effect taken into account in the statistical methods, there was a very significant windlass use effect. For both users, the results of tests with no windlass were similar in that almost every test failed. However, tests with a windlass varied by user.

The user with more experience had faster tests (mean time, 70 seconds vs. 87 seconds, $p < .0001$; 95% CI for difference, 6–27 seconds). With these shorter times to stop bleeding, the mean blood loss was also less for the user with more experience (mean volume, 458mL vs. 604mL; $p < .0001$; 95% CI for difference, 78mL–213mL). However, the users differed greatly in pressure. The mean pressure applied by the experienced user was 15mmHg, while the less-experienced user applied a mean pressure of 145mmHg ($p < .0001$; 95% CI for difference, 111mmHg–148mmHg). Based on these results, we decided it was necessary to consider the user a random effect in the mixed statistical modeling when comparing windlass type for the factors of interest: time to stop bleeding, pressure, blood loss, and blood loss per second.

Discussion

The first major finding of the present study is that the performance of improvised tourniquets varied by design, with the strap-and-windlass method performing substantially better than the strap with no windlass. Tourniquets with a windlass had higher proportions of tests with hemorrhage control, higher proportions of tests with suitable pressures, and lower rates of blood loss. Mean blood loss volumes with a windlass were more because such tests were reliably effective and lasted longer while tests with no windlass were not reliably effective and ended earlier. Use of a windlass is historically intended to gain a mechanical advantage in tightening a tourniquet. As a matter of fact, this windlass role is not specific to tourniquets but applies to hauling and lifting machines consisting of a drum or cylinder wound with a rope and turned by a crank. Windlass is an English word derived from the Old Norse language's combination of *vinda* (to wind) + *ass* (meaning pole), and windlasses are common in such varied areas as seafaring, industry, rope work, and sports that involve ropes like mountaineering. [10] In the case of improvised tourniquets, limb and strap are analogous to cylinder and rope, respectively. The role of the windlass is to gain mechanical advantage by increasing the moment arm of applied torque to twist the strap tighter.

The second major finding of the present study is that although a windlass worked when compared to no windlass, improvised tourniquet use overall was not reliable (windlass did not achieve 80% or higher effectiveness). The windlass did provide a mechanical advantage necessary to increase effectiveness, but the increase was insufficient to be reliable. The US Army experience in training tourniquet users illustrates the ineffectiveness problem with improvised tourniquets. Since 2001, the Department of Combat Medic Training, a key section of the US Army Medical Department's Center and School, made an extensive effort to train medics in improvised tourniquet use. There was a time period when the old Second World War strap-and-buckle tourniquet was out of favor within the Army, and the current standard issue Combat Application Tourniquet (Composite Resources Inc.; http://composite-resources.com) was yet to be adopted. The improvised tourniquet technique of the strap-and-windlass design was the remaining candidate for use. However, trainers assessed the improvised tourniquet as unreliable in that it could not be made reliably effective in the hands of student medics (Donald Parsons, personal communication, 2013). The experience of the Army medics, of the present investigators, and of the first responders in Boston was similar in that improvised tourniquets are challenging to use well and are unreliable in hemorrhage control. The Boston police acquired commercial tourniquets for the 2014 Boston Marathon perhaps because of the poor performance of the improvised tourniquets.[10] In 2015, Stewart et al. reviewed improvised tourniquet use and recommended their consideration for emergency use when no scientifically designed tourniquet is available, and Stewart et al improved awareness of a need for improvised tourniquets and helped legitimize research of improvised tourniquets.[12] Based on the findings of the present study, a search for better designs of improvised tourniquets is recommended; the designs that are commonly recommended or used are now shown to be unreliable. Such recommendations and uses should be reconsidered.

The first minor finding from the present study was that the improvised strap-and-windlass design showed skin deformation during use that indicated it may be more painful than a well-designed tourniquet. When the user continued to wind the knot with a windlass, the strap often dragged a fold of skin into the crease of the knot in a swirled, layered fashion. This swirling applies forceful shearing to the skin, producing damage that may cause painful pinching. Tourniquet pain varies, in part, by the tourniquet design, and there is a historical record that indicates that poorly designed tourniquets such as improvised tourniquets are more painful than well-designed tourniquets.[4,31,42] The experienced user in the present study has made thousands of tests of many different tourniquet designs and the results that appear most painful have been in the present study with the improvised strap-and-windlass design. The experienced user had treated many patients, while the inexperienced user was minimally trained in tourniquet techniques and had no healthcare experience. Because of this difference, when the expert used the windlass and the tourniquet pinched the skin severely, the user instinctively stopped the test early. The swirl avulsed fragments of silicone skin and ripped holes in the skin, which made the expert wince in empathy for the simulated casualty. The other user kept twisting the windlass until the bleeding stopped without regard for the skin deformity and damage. Without knowing the likely pain and iatrogenic injury that would have been caused if the subject was living, the less-experienced user had no such experience to limit him in twisting. Aggressively making improvised tourniquets more effective also made them less safe. The current understanding of the relationship between effectiveness and safety has not been developed fully.

The second minor finding of the present study was that tourniquets with no windlass were mostly venous tourniquets and not arterial tourniquets. The pressure applied to the skin by pulling the tee shirt tight was, on average, only 46mmHg without windlass use. This pressure is too low for a reliable arterial tourniquet but provides enough pressure to slow venous bleeding. The strap tourniquet with no windlass was modeled directly from firsthand accounts from Boston and failed 98% of the time, indicating that most such tourniquets used in Boston also likely failed to provide effective hemorrhage control. The present experiment provides clear, coherent, and concise evidence that the Boston technique was likely a venous tourniquet technique. This explanation at once explains the Boston findings, explains the experimental findings, and fulfils the purpose of the study. Education may mitigate the confusion of individual tourniquet users; improved awareness of venous versus arterial tourniquet use may aid users to become more effective.

The limitations of the present study are based in its experimental design. The results were gathered through an experiment and not through patient care. Therefore, the results are based on an assumption that the manikin acted like a bleeding patient, but the manikin has no pain response. If the inexperienced user's excessive force skewed the results toward higher effectiveness, then when patients feel pain, real-world results may be more like that of the experienced user. A controlled experiment is not as chaotic as mass casualty situations that entail other considerations such as human factors, various levels of healthcare, and tourniquet-user performance under stressful situations with associated distractions. Given these limitations, the current understanding of improvised tourniquets does not permit a definitive recommendation regarding the optimal design or best technique of use.

Future directions for research include study of other purposes, such as looking at more users to better understand user variability in skill level, looking at bystander capacity to use tourniquets, looking at learning curves of users with increasing experience by numbers of uses, and progressing to fill the many other empiric gaps in knowledge regarding improvised tourniquet use, such as which techniques are better, which device designs are better, and which training programs are better. A search for better designs of improvised tourniquets appears worthwhile. Better understanding of the effectiveness–safety relationship is needed. Once these gaps are filled by research, the user's understanding of tourniquets and of their mechanical use in first aid may be improved to move current care toward best care.

In summary, the improvised strap-and-windlass tourniquet was more effective than the same strap tourniquet with no windlass, as a windlass allowed the user to gain mechanical advantage. However, the improvised strap-and-windlass tourniquet was only 68% effective and this rate did not achieve the minimum threshold of reliability of 80%.

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Disclosure

The authors declare no conflicts of interest.

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