

Physiological Evaluation of the U.S. Army One-Handed Tourniquet

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Objective: To provide a physiological assessment of the U.S. Army one-handed tourniquet (OHT). **Methods:** An OHT was self-applied by 26 subjects, to maximal tolerable tightness, to the proximal arm or thigh under different conditions and positions, and the presence of blood flow was assessed using Doppler ultrasonography or occlusion plethysmography. **Results:** Doppler sound was eliminated at the radial artery for all subjects with OHT application but was not stopped at the popliteal or dorsalis pedis artery for any subjects. The OHT reduced forearm blood flow by 79% but decreased leg blood flow by only ~50%, regardless of condition and position of application to the thigh. **Conclusions:** The OHT appears to effectively minimize blood flow in the arm but not in the lower extremities, and clinical assessment of blood flow disappearance by Doppler ultrasonography may underestimate the magnitude of actual blood flow to the limb.

Introduction

It is estimated that 7 of 100 combat deaths would be preventable with properly applied tourniquets.^{1,2} Until recently, the only tourniquets available to soldiers were the standard strap-and-buckle tourniquet (NSN 6515-00-383-0565) and the improvised tourniquet (windlass [stick] and cravat). The former has been recognized as ineffective since World War II,³ and the latter takes excessive time to apply. The need for a rapidly deployable military tourniquet has been articulated for a half-century,⁴ and recently it was recommended that top priority be given to the development of an improved tourniquet capable of reliably stopping arterial bleeding, as well as rapid self-application with one hand.⁵

There is a need for an inexpensive, safe, low-volume/weight tourniquet in the military that is effective in controlling blood loss in extremity wounds.^{5,6} Specific design characteristics were developed based on unpublished experimental data and input from user community representatives at the U.S. Army Medical Department and U.S. Special Operations Command. It was recognized that, in meeting the desired physical tourniquet characteristics, a trade-off might be necessary, in that smaller narrower tourniquets require greater circumferential pressures for arterial occlusion⁷⁻⁹ and may be associated with an increased risk of tourniquet-related injury. As a result, a one-handed tourniquet (OHT) (NSN 6515-01-504-0827) that meets expense (approximately \$8 per unit), volume, and weight criteria has been designed, produced, and added to the U.S. Army inventory (Fig. 1). In addition, the nylon and plastic material used to manufacture the OHT provides a long shelf-life. This tourniquet system was specifically designed to be self-applied rapidly and

easily with one hand, in the event of a wound to an upper extremity that left only one hand available for tourniquet application. However, the OHT has not been tested to determine its efficacy in the occlusion of arterial blood flow when applied to either arms or legs of human subjects. Therefore, we conducted a series of experiments designed to test the effectiveness of the OHT in occluding arterial blood flow in both the upper and lower extremities. The purpose of the present investigation was to test the hypotheses that (1) self-application of the OHT to the proximal thigh or proximal arm would stop blood flow to the respective limbs; (2) if one OHT did not stop blood flow, then application of a second OHT would; and (3) reduction in blood flow to the leg with self-application to the distal thigh of a OHT saturated with fluid would be as effective as application of a dry OHT.

Methods

Subjects

All procedures and protocols were reviewed and approved by the institutional review board at Brooke Army Medical Center. After being informed of all procedures and risks, 26 healthy, normotensive, nonsmoking men and women (age range, 18–35 years) gave their written consent to serve as subjects in one of two experiments. Eleven subjects (six male subjects) participated in the initial experiment (experiment 1), and 15 additional subjects (11 male subjects) participated in the second experiment (experiment 2). Different subjects were used for the two experiments to minimize exposure time and the number of times the OHT was applied to any single subject. Before each experiment, height, weight, thigh and calf circumferences, and baseline blood pressure and heart rate were measured for each subject. Demographic data for the subjects are presented in Table I. After the subjects had changed into medical scrub clothes, designed to provide access to the arms and legs, and completed an exposure period of 20 minutes in the supine position, each subject's baseline blood flow was assessed (with Doppler ultrasonography or occlusion plethysmography) on the limb targeted for OHT application. The OHT was self-applied to maximal tolerable tightness for each evaluation. Immediately after blood flow was reassessed during OHT application, the OHT was loosened, to minimize discomfort to the subject.

Experiment 1

While the subjects were supine, the dorsalis pedis, popliteal, and radial arteries were located by auscultation and marked. At these points, Doppler ultrasonography was used qualitatively to assess the effectiveness of the OHT in stopping blood flow distal to the tourniquet. Two OHTs were placed 4 and 7 cm distal to the inguinal notch. Initially, the subject tightened the most proximal OHT on the thigh. The presence or absence of sound (pulsatile blood flow) at the dorsalis pedis and popliteal arteries was

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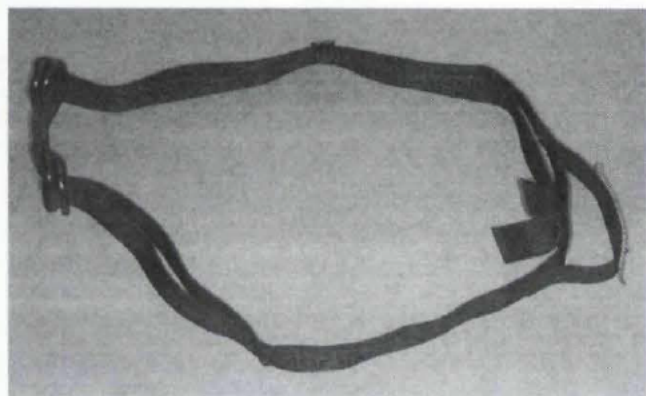


Fig. 1. OHT. The OHT is slipped over the limb. The handle is pulled, causing the excess strap to pass between the D rings and the tourniquet to be tightened.

determined (Fig. 2A). Subsequently, the subject tightened the distal OHT and assessment of the presence or absence of sound was repeated. With the experimental conditions for tourniquet application to the leg, the effectiveness of the OHT in stopping sound at the radial artery was assessed by application of the OHT around the proximal arm 5 mm distal to the deltoid insertion (Fig. 2B).

Experiment 2

Venous occlusion plethysmography was used to assess the effectiveness of the OHT in reducing or stopping blood flow to the leg and arm. The use of a Whitney strain gauge for quantitative blood flow measurements in limbs is a well-documented procedure.¹⁰⁻¹² A dual-loop, mercury-in-silastic, strain gauge was placed around the calf or forearm at the point of maximal circumference (Fig. 3). Venous outflow from the distal limb was prevented by the placement of a cuff around the thigh or arm just above the knee or elbow, using an occlusion pressure of 60 mm Hg. An ankle or wrist cuff was inflated to a pressure of 250 mm Hg for 1 minute before the occlusion of venous outflow, to isolate the circulation from the foot and hand, respectively. Venous occlusion was initiated for 10 seconds, followed by the

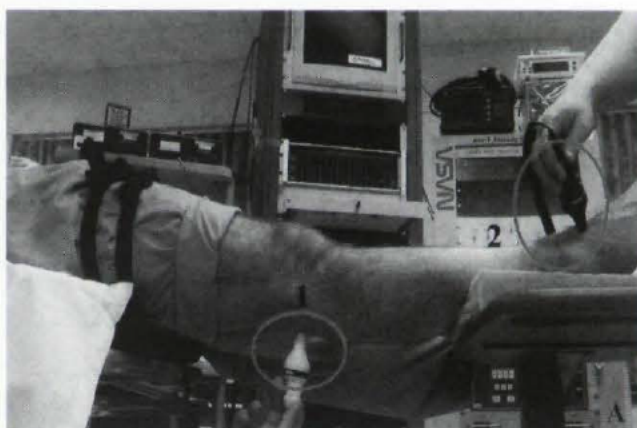


Fig. 2. Photographs depicting the experimental configuration for experiment 1. Placement of Doppler ultrasound sensors is shown at the popliteal artery (A, circle 1), dorsalis pedis artery (A, circle 2), and radial artery (B, circle). OHT placement on the thigh and arm is shown.

cuff's release for 10 seconds, for six sequential occlusions. The relative change in strain gauge length over 10 seconds was quantified as a volume of blood per unit time. The use of the thigh or arm cuff to occlude venous blood flow was not needed when the tourniquet was applied. Blood flow was determined by the change in leg or forearm volume per unit time during the initial 1 minute after application of the tourniquet (Fig. 4).

To test the effectiveness of the OHT in reducing blood flow to the limbs under varying conditions, the OHT was placed on the distal thigh (dry or saturated with water), proximal thigh (one or two OHTs applied), and proximal arm. The order of OHT condition (wet or dry) and number of OHTs applied (one or two) was counterbalanced. The OHT was positioned 6 cm proximal to the patella, 4 and 7 cm distal to the inguinal notch, and 5 mm distal to the deltoid insertion for the distal thigh, proximal thigh, and proximal arm positions, respectively.

Data Analysis

Paired *t* tests were used to compare limb blood flow values. The Bonferroni correction was used to adjust the α level of 0.05 because of multiple comparisons. No statistical analysis was performed on the Doppler data because of the lack of variance (i.e., 100% success or failure rates).

TABLE I
SUBJECT CHARACTERISTICS

	Experiment 1 (N = 11)	Experiment 2 (N = 15)
Age (years)	22 ± 1	23 ± 1
Height (cm)	174 ± 3	176 ± 2
Weight (kg)	74.4 ± 3.1	82.5 ± 2.8
Blood pressure (mm Hg)		
Systolic	112 ± 4	117 ± 3
Diastolic	61 ± 3	64 ± 3
Mean	78 ± 3	82 ± 3
Heart rate (beats per minute)	68 ± 2	67 ± 3
Circumference (cm)		
Arm	30.5 ± 0.9	32.5 ± 0.6
Distal thigh	NA	45.8 ± 0.8
Proximal thigh	60.2 ± 1.4	59.8 ± 1.0

NA, not applicable.

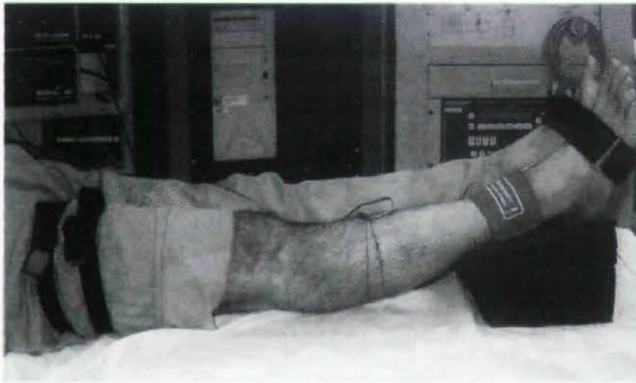


Fig. 3. Photograph depicting the experimental configuration for experiment 2. Placement of a mercury-in-silastic (Whitney) strain gauge around the calf is shown, with OHT placement on the proximal thigh.

Results

Subjects

As a group, the subjects were normotensive, active, military personnel. Their demographic data are presented in Table I. The circumference of location for placement of the OHT on the proximal thigh was approximately twice the circumference of location for placement of the OHT on the arm.

Experiment 1

The number of trials per application of the OHT that resulted in the absence of Doppler sound (blood flow) at the radial, dorsalis pedis, and popliteal arteries is presented in Table II. The OHT was successful in stopping Doppler sound at the radial artery for all 11 subjects when applied to the proximal arm. In contrast, the OHT failed to eliminate Doppler sound at the popliteal or dorsalis pedis artery for any of the 11 subjects when either one or two OHTs were applied to the proximal thigh.

Experiment 2

The relative reductions ($\% \Delta$) in blood flow resulting from OHT application to the leg and arm are presented in Figures 5 and 6. When applied to the proximal arm, the OHT reduced blood flow from $2.9 \pm 0.2 \text{ ml} \times \text{dl}^{-1} \times \text{min}^{-1}$ at baseline to $0.6 \pm 0.1 \text{ ml} \times \text{dl}^{-1} \times \text{min}^{-1}$ after OHT application ($t = 10.69$, $p < 0.0001$). When applied to the proximal thigh, the OHT reduced blood flow from $2.2 \pm 0.2 \text{ ml} \times \text{dl}^{-1} \times \text{min}^{-1}$ at baseline to $0.9 \pm 0.1 \text{ ml} \times \text{dl}^{-1} \times \text{min}^{-1}$ after application of either one or two OHTs ($t > 5.73$, $p < 0.0001$). Finally, baseline blood flow was reduced from $2.1 \pm 0.2 \text{ ml} \times \text{dl}^{-1} \times \text{min}^{-1}$ at baseline to $0.9 \pm 0.1 \text{ ml} \times \text{dl}^{-1} \times \text{min}^{-1}$ ($t = 5.87$, $p < 0.0001$) when a dry OHT was applied to the distal thigh, compared with $1.0 \pm 0.1 \text{ ml} \times \text{dl}^{-1} \times \text{min}^{-1}$ ($t = 4.72$, $p < 0.0003$) when a wet OHT was applied to the distal thigh.

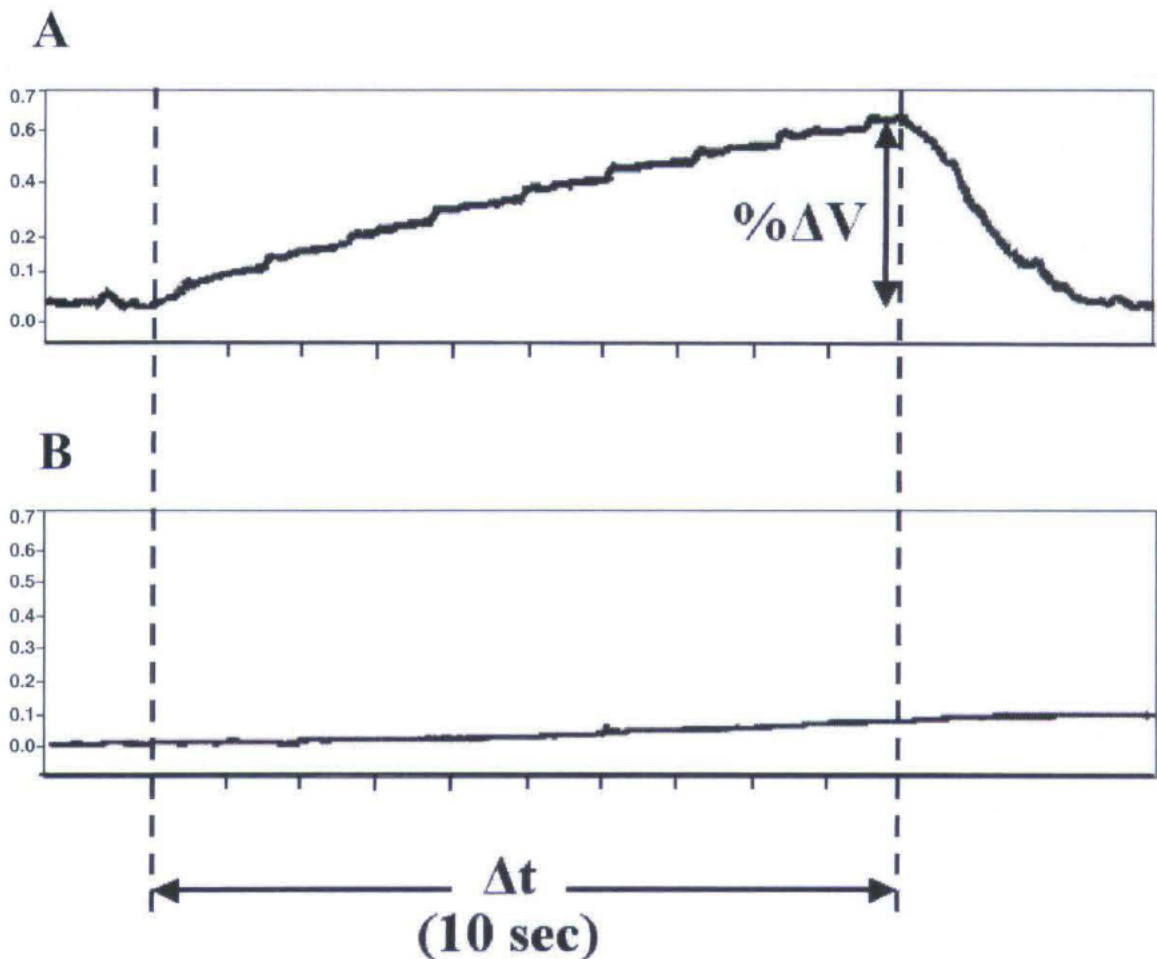


Fig. 4. Plethysmographic record from the arm of a subject, demonstrating a typical recording of the increase in strain gauge circumference ($\% \Delta V$) over a 10-second time interval (Δt), without (A) and with (B) application of the OHT. Blood flow is calculated as the ratio $\Delta V / \Delta t$.

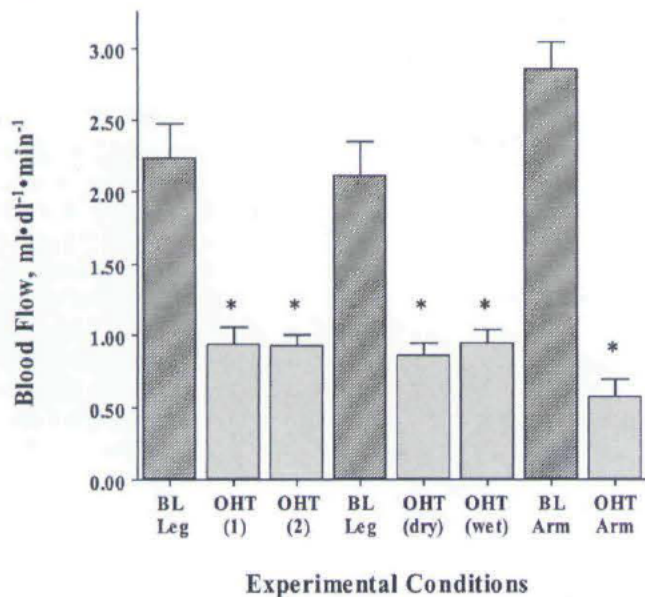


Fig. 5. Mean (\pm SE) blood flow data during baseline (BL) conditions for the leg (Leg) and arm (Arm) (hatched bars) and during applications of the OHT (stippled bars) under conditions of a single OHT applied on the proximal thigh (1), two OHTs applied on the proximal thigh (2), a dry OHT applied on the distal thigh (dry), a wet OHT applied on the distal thigh (wet), and an OHT applied on the proximal arm (Arm). * $p < 0.0003$, compared with the corresponding baseline condition.

Relationships between Limb Circumference and Blood Flow Occlusion

In general, smaller average limb circumference of the upper extremity was related to greater relative reduction in blood flow during application of the OHT, as indicated by average blood flow reductions of 79% in the arm and 49% to 55% in the leg. This corresponded to average arm and proximal thigh circumferences of 32.5 and 59.8 cm, respectively. However, correlation coefficients calculated from individual limb circumferences and relative (% Δ) reductions in blood flow were 0.064 for the arm and 0.218 for the leg.

Discussion

OHT Application to the Arm

The primary objective of any tourniquet is to occlude arterial blood flow. Previous evaluation of possible tourniquets for combat far-forward settings established the criterion that a tourniquet must occlude detectable (Doppler) blood flow in at least 75% of the subjects in order for the device to be considered successful.⁶ The specific requirement for a tourniquet that can be self-applied with one hand may be important for application to an upper extremity wound when the hand of the injured limb is not functional. From this standpoint, OHT application to the upper extremity appears to meet the criteria for a relatively effective approach for occluding blood flow in the arm. This notion was supported by the results from our study that demonstrated that 100% of our subjects were able to arrest detectable blood flow with OHT application to the proximal arm, as determined by Doppler auscultation. The absence of Doppler sound with OHT application to the proximal arm corresponded to ~80% reduction in average forearm blood flow. This 80% reduction in blood flow to the distal arm could be of great

TABLE II
OHT SUCCESS RATE USING DOPPLER AUSCULTATION AT DIFFERENT ARTERIAL LOCATIONS

	Dorsalis	Popliteal	Radial
One OHT, proximal thigh	0/11	0/11	NA
Two OHTs, distal thigh	0/11	0/11	NA
OHT, arm	NA	NA	11/11

NA, not applicable.

significance in the event of an upper-extremity injury. Because a 50% loss of a total blood volume of ~6 L (i.e., ~3 L) is acutely life-threatening,¹³ we could expect a soldier with an arterial arm injury who loses 100 mL of blood per minute to "bleed out" in ~30 minutes in the absence of tourniquet application. If the normal blood loss from such a wound could be reduced by 80%, as indicated by the results of the present investigation, then the time required to reach 50% blood volume loss (i.e., bleed out) would be increased by 120 minutes. Thus, OHT application to a major arterial wound to the arm could be expected to "buy" as much as 2 additional hours for the soldier to receive the definitive care that could save his or her life. This could be the worst-case scenario, because the reduced blood flow might allow spontaneous coagulation or effective control with hemostatic dressings to stop blood loss completely.

OHT Application to the Leg

In contrast to the arm, OHT application to the leg failed to stop detectable blood flow (Doppler auscultation) for any of the subjects. The presence of Doppler sound with OHT application to the thigh corresponded to a reduction in average leg blood flow of only ~50%. Although the blood flow to one leg is ~0.3 L/min at rest,¹⁴ bleeding from a severe wound can be exacerbated for a

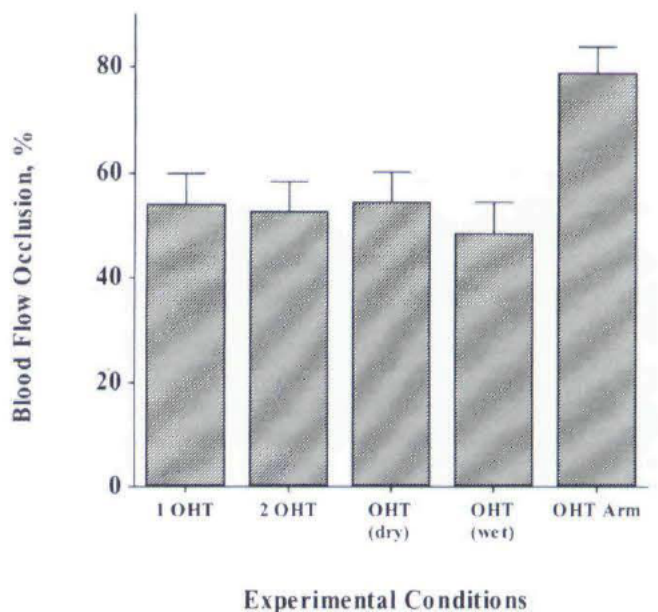


Fig. 6. Mean (\pm SE) percentage of blood flow occluded after applications of the OHT under conditions of a single OHT applied on the proximal thigh (1), two OHTs applied on the proximal thigh (2), a dry OHT applied on the distal thigh (dry), a wet OHT applied on the distal thigh (wet), and an OHT applied on the proximal arm (Arm).

soldier engaged in combat (i.e., during mild physical activity), when blood flow in the leg can be increased 5- to 10-fold.¹⁴ Therefore, depending on the physical activity required during combat conditions, a wounded soldier with a severe hemorrhage wound and blood flow of 1.0 to 1.5 L/min in the leg may bleed out (i.e., lose 3 L of blood) in as few as 2 minutes. The results of this investigation indicate that immediate application of the OHT may perhaps double this time. Under this scenario, it is unlikely that the additional 2 minutes would result in a life-saving measure.

A recent panel of experts¹⁵ questioned the specific requirement for a tourniquet that can be self-applied to a bleeding arm wound with the uninjured hand. The panel was concerned that the design requirement for one-handed operation might be incompatible technically with the ability to occlude arterial flow in the lower limb adequately. This is because the pressure required to occlude blood flow in a limb increases exponentially with the circumference of that limb.^{7,9,16} Therefore, the lower limb requires much greater tourniquet pressure to occlude blood flow than does the upper limb. However, the vast majority of the battlefield wounds requiring tourniquet application occur in the lower limb, where both hands should be available for tourniquet application.¹⁷ Therefore, it is much more important that a battlefield tourniquet first be able to occlude arterial flow in the lower extremity.³ In an earlier survey, Calkins et al.⁶ identified two strap-type tourniquets that did provide satisfactory arterial occlusion; both used a ratchet device with a 1.75-inch strap. However, neither was compatible with one-handed operation.

It is likely that the relatively narrow width (1 inch) of the OHT was a primary contributor to its inability to stop leg blood flow effectively. Previous investigators demonstrated clearly an inverse relationship between tourniquet width and minimal pressure required to occlude arterial blood flow.⁷⁻⁹ That is, as the width of the tourniquet decreases, the pressure required to occlude arterial blood flow increases exponentially. Furthermore, as introduced previously, the pressure required to occlude blood flow in a limb increases exponentially with the circumference of that limb.^{7,9,16} Therefore, it was not unexpected that the OHT was more effective in occluding blood flow in the arm, which is approximately one-half the circumference of the leg. However, there existed great variability in blood flow occlusion within the same limb (e.g., arm) across subjects, suggesting that factors other than limb circumference per se contributed (e.g., subject strength, subject intolerance to discomfort, and tissue composition).

Based on the relationship between tourniquet width and occlusion pressure described above, it might seem that the ineffectiveness of the OHT could be addressed by increasing the width of the strap. However, wider straps cause more friction through the D-rings and consequently prohibit pressure development in the tourniquet. Also, as width increases, the amount of tissue that must be compressed increases, greatly increasing the effort required to produce tension.¹⁸ Taken together, these two factors likely would further reduce the effectiveness of the OHT. It is theoretically possible to attain adequate occlusion pressure by using a 1-inch-wide tourniquet augmented with a mechanism that provides a mechanical advantage, such as a ratchet system. However, such a system could produce significant tissue damage. A wider tourniquet using a mechanism

other than that used in the OHT should be pursued in future development of an improved tourniquet for combat use.

Relationship between Doppler Sounds and Blood Flow

Assessment of the presence of sound from Doppler ultrasound probes placed on arteries is a common method used by physicians to determine blood flow in extremities. With the use of occlusion plethysmography, a more sensitive technique, we demonstrated that a minimum of ~20% of baseline blood flow can be present in the absence of Doppler sound. Because the presence of sound obtained from Doppler auscultation relies on the presence of pulses, our results may reflect a pressure generated by OHT application that eliminates pulsatile blood flow but allows nonpulsatile flow. Our observations provide evidence that Doppler auscultation may overestimate the effectiveness of a clinical procedure designed to occlude blood flow (e.g., a tourniquet) and may underestimate the actual amount of blood flow present.

Conclusions

There is an urgent need for an effective tactical tourniquet that can be rapidly self- or buddy-applied for soldiers under fire. The current Army OHT represents a step toward satisfying that need. Although the OHT is effective when applied to the arm, the inability of the OHT to occlude arterial blood flow in the lower extremity, when tightened to a pain threshold, emphasizes the need for continued development of tourniquet systems that can meet weight and volume requirements without sacrificing effectiveness and safety. We suggest that one-handed application, although desirable, should be secondary to effective arterial occlusion. Future designs for battlefield tourniquets must balance the need to meet size and weight requirements with established principles of tourniquet design.

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