Tourniquets and Occlusion: The Pressure of Design

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ABSTRACT Nerve injuries result from tourniquet pressure. The objective was to determine arterial occlusion and completion pressures with the 3.8-cm-wide windlass Combat Application Tourniquet (CAT) and the 10.4-cm-wide Stretch, Wrap, and Tuck Tourniquet (SWAT-T). Methods: Sixteen volunteers self-applied and had tourniquets applied to their thighs and arms (CAT and SWAT-T, random order, then blood pressure cuffs). Results: Occlusion (Doppler signal elimination) pressures were higher than predicted ($p < 0.0001$), highest with the CAT ($p < 0.0001$), and often lower than completion pressures (completion median, range: CAT 360, 147–745 mm Hg; SWAT-T 290, 136–449 mm Hg; cuff 184, 108–281 mm Hg). Three CAT thigh and 9 CAT arm completion pressures were >500 mm Hg. Pressure decreases and occlusion losses occurred over 1 minute (pressure decrease: CAT 44 ± 33 mm Hg; SWAT-T 6 ± 8 mm Hg; cuff 14 ± 19 mm Hg; $p < 0.0001$; loss/initially occluded: CAT 17 of 61, SWAT-T 5 of 61, cuff 40 of 64, $p < 0.01$). CAT pressures before turn did not have a clear relationship with turns to occlusion. Conclusions: Limb circumference/tourniquet width occlusion pressure predictions are not good substitutes for measurements. The wider SWAT-T has lower occlusion and completion pressures than the CAT. Decreases in muscle tension lead to decreases in tourniquet pressure, especially with the nonelastic CAT, which can lead to occlusion loss.

INTRODUCTION

Tourniquets are an important part of tactical medicine and are recognized as having a place in civilian prehospital care.[1–8] Current understanding of tourniquet science is that circumferential compression of a longer section of limb (wider or side-by-side tourniquets) should result in cessation of arterial flow at lower pressures than needed with compression of a shorter section of limb.[4–6,9] Lower pressure arterial occlusion and lower completed tourniquet pressure are desirable for avoiding nerve damage.[6,10] Design widths are limited, however, by the need to achieve adequate circumferential pressure on an increasing volume of tissue with acceptable pressure distribution across the tourniquet's width.

With a long history of surgical use,[11] pneumatic tourniquets such as standard blood pressure cuffs and the Emergency Medical Tourniquet (EMT; Delfi Medical Innovations, Vancouver, BC, Canada) are relatively wide but may not be sufficiently robust for deployment and use in some tactical environments.[4,6,12] Standard blood pressure cuffs are designed for transient occlusion of arterial flow. The EMT is designed for minutes to hours of arterial occlusion. The amount of pressure exerted using a pneumatic design can generally be limited to that at which arterial occlusion occurs.

With an even longer history of surgical use,[11] stretch and wrap tourniquets such as the Esmarch and the Stretch, Wrap, and Tuck Tourniquet (SWAT-T; TEMS Solutions, Abingdon, Virginia) come in a variety of widths. The SWAT-T is wider than the pneumatic EMT and is designed for deployment and use in a tactical environment. Depending on the method used to secure the free end, it may not be simple to limit the amount of pressure exerted using a stretch and wrap design to that at which arterial occlusion occurs.

Windlass or "stick and strap" tourniquets have been used in military and emergency settings for hundreds of years.[11] The 2 commercially sold windlass designs commonly deployed with and used by United States military personnel, the Combat Application Tourniquet (CAT; Composite Resources, Rock Hill, South Carolina) and the Special Operations Forces Tactical Tourniquet (SOFTT; Tactical Medical Solutions, Anderson, South Carolina), are less wide than either the EMT or the SWAT-T.[4] Because the stick part of the design must be secured, it may not be possible to limit the amount of pressure exerted using a windlass design to that at which arterial occlusion occurs.

As mentioned, achieving arterial occlusion and tourniquet completion at lower pressures is desirable for avoiding nerve damage.[10] Data concerning the pressures applied with commercially produced, tactical environment tourniquets are lacking. The purpose of this study was to collect occlusion and completion pressures with different widths and styles of tourniquets designed for tactical environment use. The two main hypotheses were that (1) arterial occlusion pressures would be lower with wider designs and (2) tourniquet completion pressures with the stretch and wrap design (SWAT-T) and the windlass design (CAT) would be higher than the pressure required for arterial occlusion.

METHODS

This prospective study was approved by the Drake University Institutional Review Board. The pneumatic blood pressure cuffs were provided by Drake University and Iowa Methodist Medical Center. The SWAT-T's and the CAT's were purchased.

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Tourniquets

The pneumatic tourniquets were a standard adult blood pressure cuff and a longer adult blood pressure cuff. The standard blood pressure cuff (AllHeart, Louisiana, Missouri) was 278 g, 14.5 cm wide, 53 cm long, had several parts (bladder with 2 tubes, fabric containing bladder, manometer, squeeze bulb for inflation, and valve between squeeze bulb and tube to hold or release air), and cost U.S. $15.98. The longer blood pressure cuff (Hokanson, Bellevue, Washington) was 288 g, 13.3 cm wide, 83 cm long, and had several parts (bladder with 1 tube, fabric containing bladder, stopcock to connect bladder's single tube to a manometer and a squeeze bulb for inflation, valve between squeeze bulb and stopcock to hold or release air) and cost U.S. $36. The SWAT-T's were 95 g, 10.4 cm wide, 11.7 cm circumference rolled up, 150 cm unrolled; had only 1 part; and cost U.S. $8.50. The CAT's were 59 g, 3.8 cm wide, 92.5 cm long; had several integrated parts (strap, "ribbon" running inside the strap and through the "stick," friction buckle, plate, "stick," "stick" securing pieces); and cost U.S. $35.33.

Pressure Measurements

Pressures under tourniquets were determined using a #1 neonatal blood pressure cuff (2.2-cm-wide bladder, 6.5-cm-long bladder, single tube) (Tru-Cuff, SpaceLabs Healthcare, Issaquah, Washington). The air-filled neonatal cuff was taped to the skin, and the tourniquets were applied over it (similar to the methods of Biehl et al[13] and Grebing and Coughlin[14]). The inflated neonatal cuff was connected to a gas pressure sensor system (Vernier Gas Pressure sensor, Vernier LabPro interface, and Logger Pro Software; Vernier Software and Technology, Beaverton, Oregon). The resulting displayed pressure values were recorded from the computer screen.

Occlusion pressures were recorded when the distal arterial Doppler pulse signal (Ultrasonic Doppler Flow Detector Model 811 with 9.5 MHz adult flat probe; Parks Medical Electronics, Aloha, Oregon) became inaudible (wrist radial artery or ankle posterior tibial artery). Completion pressures were recorded when the applier's hands were off the secured tourniquet. Loss of occlusion pressures were recorded if the Doppler pulse signal became audible after occlusion but before the 1-minute-after-completion removal. Prerelease pressures were recorded just before removal. When the CAT was used, pressures were also recorded after the strap was secured but before any turns of the stick.

Pressure Measurement System Comparisons

First, two pressure sensors were connected to the standard adult blood pressure cuff. Comparison readings were taken with the cuff laying flat with the squeeze bulb valve open, then with the cuff inflated to 50, 100, 150, 100, and 50 mm Hg according to the manometer that was an integrated part of the cuff, and then again with the squeeze bulb valve open. The sequence was repeated. Higher pressures were not used to avoid ripping the seams of the fabric surrounding the cuff's rubber bladder.

Second, one of the sensors was attached to the adult cuff, and the other was attached to the neonatal cuff. The adult cuff was placed around a volunteer's arm (mid-brachium) over the neonatal cuff. Readings from both were taken with the squeeze bulb valve open, then with the cuff inflated to 50, 100, 150, 200, 250, 300, 250, 200, 150, 100, and 50 mm Hg according to the manometer that was an integrated part of the adult blood pressure cuff, and then again with the squeeze bulb valve open. The sequence was repeated.

Subjects

Volunteers were undergraduate students and college instructors. The inclusion criterion for tourniquet recipients and tourniquet appliers was knowledge of the project via involvement in a course involving physiology-related research. The exclusion criteria for tourniquet recipients were any self-reported clotting or circulation abnormalities, blood pressure problems, or pain syndromes, or peripheral neuropathies. There were no exclusion criteria for tourniquet appliers.

Tourniquet appliers trained with the adult blood pressure cuffs with a certified Emergency Medical Technician. Volunteers trained with the SWAT-T and CAT with the manufacturer's printed instructions, PowerPoint slides from the manufacturer's Website (CAT), and training videos posted on the internet (SWAT-T and CAT). All were supplied with tourniquet-related reading and were directed to pay special attention to Ref. 4 regarding proper application of the CAT. Volunteers trained on multiple occasions and were engaged in technique discussions. Application techniques were visually assessed by the authors during training sessions and during the experiments. Verbal feedback was given to tourniquet appliers during training sessions, and technique correctness was monitored during the experiments (slack removal, appropriate friction buckle threading according to one- or two-handed application, and correct orientation of chamfered slot in the stick for the CAT; appropriate and maintained stretch and overlying wraps for the SWAT-T).

All tourniquet recipients applied the tourniquets to themselves. All tourniquet recipients then also had the tourniquets applied to them by another person (nonself-applier).

Protocol

One week after final training, nonself-appliers and recipients (sitting in T-shirts and shorts) completed the study protocol.

(1) The recipient information shown in Table I was collected.
(2) Either the SWAT-T or the CAT was used first (randomized order). Each application included 1 minute from completion to removal and 2 minutes between removal and the next application. In order of occurrence, the tourniquet was self-applied on the dominant side mid-thigh (thigh), self-applied on the dominant side mid-brachium (arm), applied by the nonself-applier on the nondominant side thigh, and applied by the same nonself-applier on the nondominant side arm.

TABLE I. Characteristics of Tourniquet Recipients

	Males (n = 6)	Females (n = 11)
	Median, Range	Median, Range
Age (years)	22, 19–23	22, 19–51
Height (cm)	179, 172–184	165, 147–181
Weight (kg)	83, 68–109	70, 52–84
Mid-Thigh Circumference (cm) (total n = 33)[a]	48, 39–56	48, 41–56
Mid-Brachium Arm Circumference (cm) (total n = 33)[a]	30, 28–33	28, 23–32
Right Arm Systolic Pressure (mm Hg)	114, 108–140	118, 102–130
Right Arm Diastolic Pressure (mm Hg)	60, 56–75	60, 50–80
Overhead Press (kg)	44, 41–64	23, 16–32
Seated Row (kg)	90, 77–109	57, 36–68

[a]Only the right thigh and arm circumferences were measured on the recipient for the muscle tension experiments.

(3) The sequence was repeated with the second tourniquet (CAT or SWAT-T).
(4) The blood pressure cuffs were applied by the same nonself-applier to the recipient's dominant side thigh, dominant side arm, nondominant side thigh, and nondominant side arm.

Data Collected During Protocol

Pressure readings from the air-filled bladder under the tourniquets and from the adult blood pressure cuff manometer were collected. The number of SWAT-T wraps for completion were recorded (full wrap of limb circumference = 1 wrap). The number of CAT stick turns were recorded (first 90° turn to reach parallel with the strap = 0, each 180° turn thereafter = 1 turn). After every application, ease and discomfort ratings were obtained.[15,16]

Predicted Occlusion Pressures

After Protocol completion, the following equation was used to calculate predicted occlusion pressures:

$$\text{Predicted Occlusion Pressure} = (\text{Limb Circumference}/\text{Tourniquet Width}) \times 16.67 + 67$$

The equation came directly from Ref. 4 and was developed from the work of Graham et al.[9]

Additional Experiments

We observed marked pressure decreases under the CAT during the 1 minute between completion and tourniquet removal. We had not expected such under a nonelastic webbing. We believed changes in muscle tension might have been responsible and therefore did the following additional experiments.

To determine the effect of muscle tension and relaxation, the CAT and then SWAT-T were applied (nonself) to the right arm and the right thigh. Then the standard adult blood pressure cuff was applied to the right arm. Occlusion and completion pressures were recorded; then pressures were recorded with the tourniquet limb relaxed for 10 seconds, tensed for 10 seconds, relaxed 10 seconds, tensed 10 seconds, relaxed 10 seconds, and tensed for a final 10 seconds.

Statistical Analysis

Pressure data were analyzed using paired and unpaired t tests, one-way ANOVA, linear regression, or Pearson correlations. Contingency tables (occlusion loss, ease, and discomfort) were analyzed using χ^2 test. Graphing and statistical analyses were done using GraphPad Prism version 5.02 for Windows (GraphPad Software, San Diego, California). Means are shown ±standard deviation. Whiskers on plots show the range. Statistical significance was set at $p \leq 0.05$. The p values are given when <0.10.

RESULTS

There were 17 recipients (Table I) and 16 nonself-appliers.

Pressure Measurement System Comparisons

All readings for two sensors connected to the adult cuff were within 3.0 mm Hg of each other. With the cuff inflated on a table, the recorded sensor pressures were higher than the pressures targeted on the integrated cuff manometer by 9 ± 9 mm Hg (linear regression $y = 1.075(x) + 4.5$, $R^2 = 0.98$).

During cycling from 0 to 300 to 0 mm Hg around a volunteer's arm, the sensor readings from the adult cuff were 10 ± 3 mm Hg higher than the targeted blood pressure cuff manometer values ($y = 1.025(x) + 6.2$, $R^2 = 1.00$). Values recorded from the sensor attached to the neonatal cuff underneath the adult cuff were more variable with a difference of 5 ± 15 mm Hg from the sensor attached to the adult cuff ($y = 0.9937(x) + 6.1$, $R^2 = 0.98$). Comparisons of the 163 available paired pressure measurements taken during the Protocol from the adult cuff manometer and the sensor attached to the neonatal cuff generally showed higher pressures recorded from the neonatal cuff sensor than from the manometer of the overlying adult cuff (157 values higher, 6 values lower, average difference of 38 ± 21 mm Hg, Pearson $r = 0.84$, $p < 0.0001$).

Application Pressures

As shown in Figures 1 and 2, actual occlusion pressures were higher and more varied than predicted occlusion pressures with each tourniquet ($p < 0.0001$). Also, CAT pressures were higher than SWAT-T and pneumatic pressures ($p < 0.0001$) and included pressures greater than 500 mm Hg. Completion pressures with the CAT and SWAT-T were generally higher than occlusion pressures ($p < 0.01$). Except for SWAT-T arm applications, self-application occlusion, completion, and 1 minute pressures with the CAT and SWAT-T

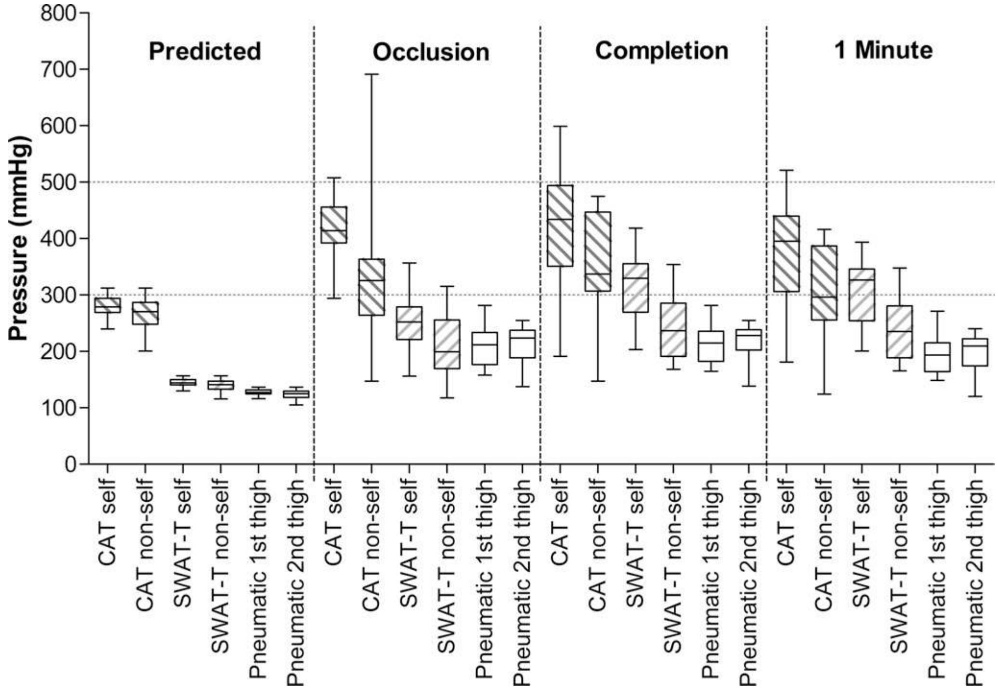

FIGURE 1. Thigh tourniquet pressures. $p < 0.0001$ for predicted thigh pressures versus respective occlusion pressures. $p < 0.0001$ for CAT occlusion, completion, and 1-minute thigh pressures versus respective SWAT-T and pneumatic pressures. $p < 0.0001$ for SWAT-T completion and 1-minute thigh pressures versus respective pneumatic pressures. $p = 0.017$ for CAT occlusion thigh pressures versus all CAT completion thigh pressures. $p < 0.0001$ for SWAT-T occlusion thigh pressures versus SWAT-T completion thigh pressures. $p = 0.0017$ for self versus nonself-CAT occlusion, completion, and 1-minute thigh pressures. $p < 0.0001$ for self versus nonself-SWAT-T Occlusion, Completion, and 1 Minute thigh pressures. $p < 0.0001$ for CAT completion thigh pressures versus CAT 1-minute thigh pressures. $p = 0.0053$ for SWAT-T completion thigh pressures versus SWAT-T 1-minute thigh pressures. $p < 0.0001$ for pneumatic completion thigh pressures versus pneumatic 1-minute thigh pressures.

tended to be higher than nonself-applier occlusion, completion, and 1 minute pressures ($p < 0.01$). Pressure losses occurred between completion and 1 minute ($p < 0.01$), and the largest of these occurred with the CAT (Table II). Despite pressure losses, some CAT 1-minute values were still greater than 500 mm Hg (Table II).

Arterial Occlusion

Most tourniquet applications resulted in arterial occlusion as measured by loss of the audible Doppler signal (Table III). Intolerable discomfort during two CAT thigh applications resulted in failures of occlusion maintenance because of removal in one case and a pain related inability to advance the windlass to a secure point past the occlusion point in the other. Physical inability to advance the windlass to a secure point past the occlusion point resulted in failure of occlusion maintenance in a third CAT thigh application. The remainder of the failures were from not achieving arterial occlusion (3 CAT and 3 SWAT-T) or from a return of arterial flow before 1 minute despite being completed with arterial occlusion (14 CAT, 5 SWAT-T, and 40 pneumatic blood pressure cuff applications, $p < 0.01$ for CAT versus SWAT-T and for CAT versus pneumatic). Of the SWAT-T failures, one self-applied arm application (failure to achieve arterial occlusion) and one other-applied arm application (failure to maintain arterial occlusion) were associated with visually inadequate stretch during the application. All tourniquet applications were observed with visible correctness data collected, and no other SWAT-T applications and no CAT applications had technique faults noted.

The individual values of most thigh CAT completion and 1-minute pressures that lost occlusion were scattered inside the range created by the individual values of CAT completion and 1-minute pressures that maintained occlusion (Fig. 3, only 2 lost occlusion values were below the lowest value for maintained occlusion). This was not the case for SWAT-T pressures. The completion and 1-minute pressures of the 3 thigh SWAT-T applications that lost occlusion were at least 7 mm Hg below the lowest completion or 1-minute pressure value that maintained occlusion (Fig. 3). The individual completion and 1-minute pressures of the pneumatic tourniquet applications that lost occlusion were mostly within the range of values for those that maintained occlusion.

Fewer arm than thigh CAT and SWAT-T applications lost occlusion (Table III). The spread of individual values for arm CAT completion and 1-minute pressures that maintained occlusion (144–745 mm Hg) was even wider than for individual thigh CAT applications (Figs. 3 and 4). The pressure values at completion and at 1 minute for the 4 arm CAT applications that lost occlusion were inside the range created by those arm CAT applications that maintained occlusion (Fig. 4). The pressures

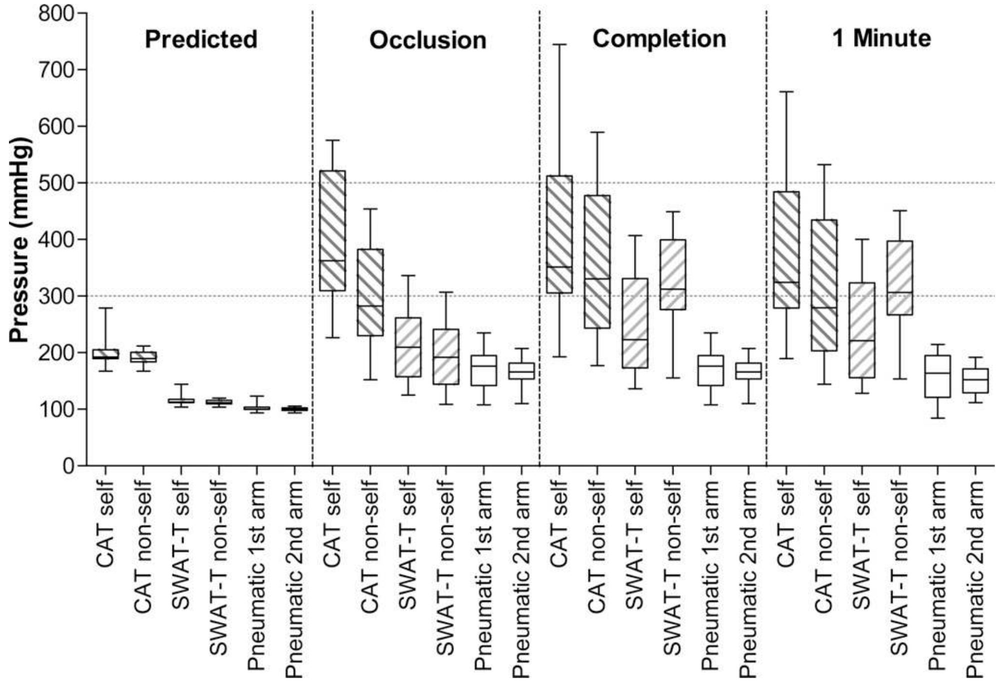

FIGURE 2. Arm tourniquet pressures. $p < 0.0001$ for predicted arm pressures versus respective occlusion pressures. $p < 0.0001$ for CAT occlusion, completion, and 1-minute arm pressures versus respective SWAT-T and pneumatic pressures. $p < 0.0001$ for SWAT-T completion and 1-minute arm pressures versus respective pneumatic pressures. $p = 0.0857$ for CAT occlusion arm pressures versus CAT completion arm pressures. $p < 0.0001$ for SWAT-T occlusion arm pressures versus SWAT-T completion arm pressures. $p = 0.0025$ for self versus nonself CAT occlusion, completion, and 1-minute arm pressures. $p < 0.0044$ for self versus nonself-SWAT-T occlusion, completion, and 1-minute arm pressures. $p < 0.0001$ for CAT completion arm pressures versus CAT 1-minute arm pressures. $p < 0.0001$ for SWAT-T completion arm pressures versus SWAT-T 1-minute arm pressures. $p < 0.0040$ for pneumatic completion arm pressures versus pneumatic 1-minute arm pressures.

for the 4 were, however, in the lower half of that range. The pressure values at completion and at 1 minute for the 2 arm SWAT-T applications that lost occlusion were inside the range created by those arm SWAT-T applications that maintained occlusion. The 2 were, however, in the lower half of that range. The individual completion and 1-minute pressures of the pneumatic tourniquet applications that lost occlusion were also within the range of values for those that maintained occlusion.

TABLE II. Tourniquet Pressure Losses Over 1 Minute

Tourniquet	Self- and Nonself-Combined Limbs	Pressure Loss (mm Hg)	1-Minute Values (>300 mm Hg)	1-Minute Values (>500 mm Hg)
CAT	Thighs ($n = 32$)	*49 ± 39	19	2
CAT	Arms ($n = 32$)	*40 ± 27	17	4
SWAT-T	Thighs ($n = 32$)	5 ± 10	13	0
SWAT-T	Arms ($n = 32$)	6 ± 6	13	0
Pneumatic	Thighs ($n = 32$)	14 ± 12	0	0
Pneumatic	Arms ($n = 32$)	14 ± 24	0	0

*$p < 0.0001$ CAT versus SWAT-T and pneumatic.

TABLE III. Tourniquet Arterial Occlusion

	Reached Occlusion			Lost Occlusion*		
	CAT	SWAT-T	Pneumatic	CAT	SWAT-T	Pneumatic
Self-Thigh ($n = 16$)	15	15	16	5	0	12
Nonself-Thigh ($n = 16$)	15	14	16	8	3	10
Self-Arm ($n = 16$)	16	16	16	1	1	8
Nonself-Arm ($n = 16$)	15	16	16	3	1	10

*$p < 0.01$ CAT versus SWAT-T and for CAT versus pneumatic.

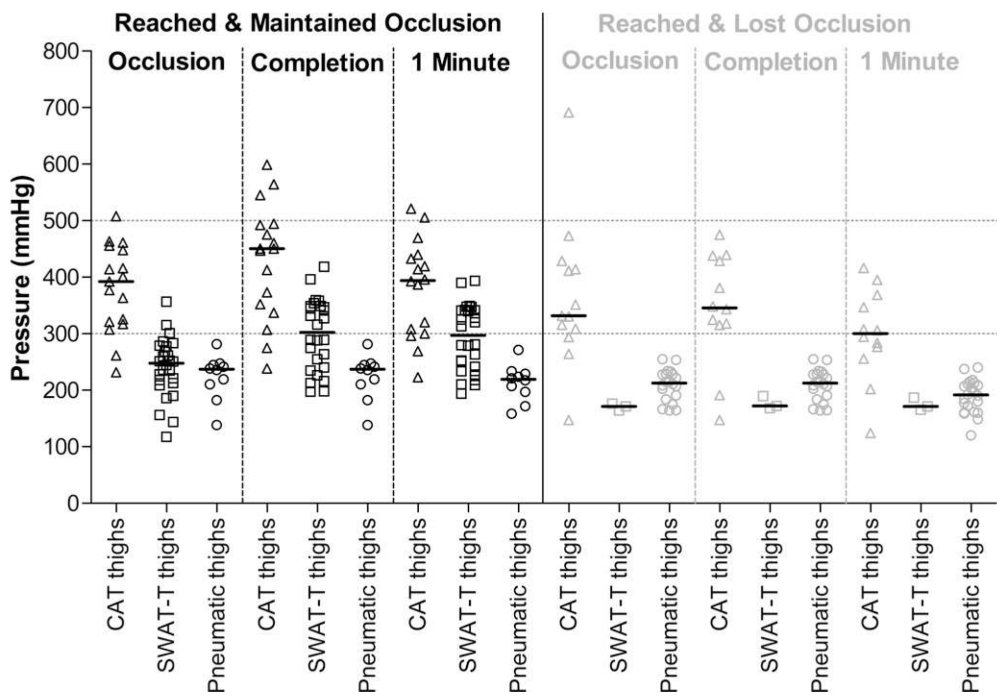

FIGURE 3. Thigh tourniquet pressures organized by occlusion. Pressures under 300 mm Hg are considered relatively safe[4,6] and those over 500 mm Hg are unsafe.[10]

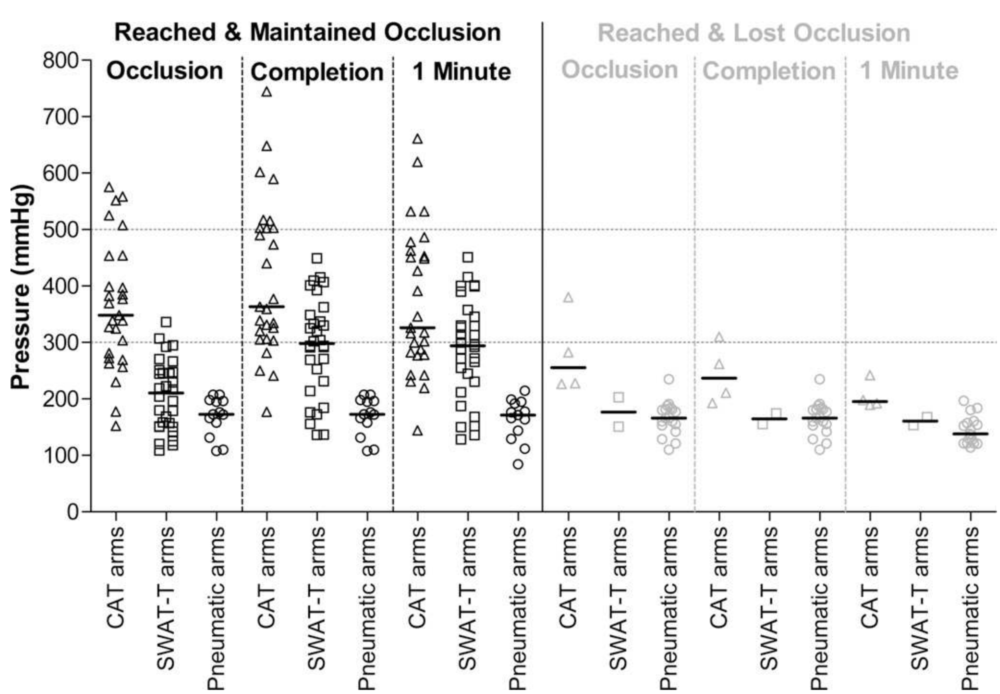

FIGURE 4. Arm tourniquet pressures organized by occlusion. Pressures under 300 mm Hg are considered relatively safe[4,6] and those over 500 mm Hg are unsafe.[10]

Pre-Windlass Pressures and Number of CAT Turns

No strong relationships appeared between the pressure exerted by the hook and loop and friction buckle secured band of the CAT before any windlass turns, the number of turns used to complete the tourniquet application, and the reaching or maintaining of occlusion (Figs. 5 and 6). The highest pre-windlass pressures were recorded during self-applications to the arm (one-handed strap routing, which appliers found easier to tension than the two-handed strap routing through the friction buckle). Thigh applications

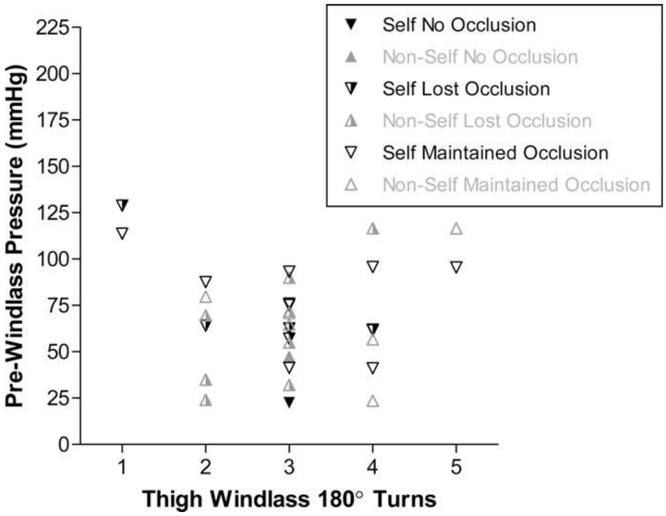

FIGURE 5. Thigh CAT pre-windlass strap pressures versus windlass turns and occlusion. Failures to reach or maintain occlusion occurred within the same range of pre-windlass strap pressures as maintained occlusion. Pre-windlass strap pressures did not seem to have a bearing on the number of turns used.

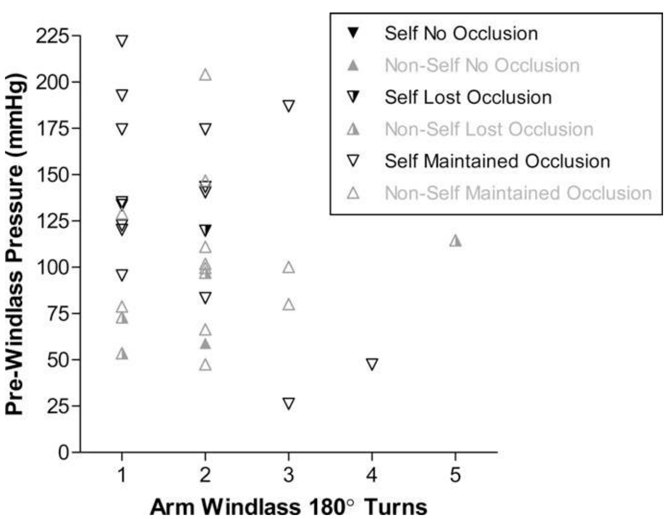

FIGURE 6. Arm CAT pre-windlass strap pressures versus windlass turns and occlusion. Failures to reach or maintain occlusion occurred within the range of pre-windlass strap pressures with maintained occlusion (but failures only occurred in the lower half of the range). Pre-windlass strap pressures did not seem to have a bearing on the number of turns used.

tended to require more windlass turns than arm applications. Despite visually correct applications and confirmatory pressure evidence of the removal of slack, quite a few applications required more than 3 turns to reach occlusion, especially on the thigh.

Number of SWAT-T Wraps

No relationships were observed between the number of wraps and occlusion failures. Weak relationships were observed between the number of wraps and the completion pressures (thighs Pearson $r = 0.53$, $p = 0.0017$; arms Pearson $r = 0.40$, $p = 0.0237$). Thighs received 3 to 5 wraps (median and range: 4.6 and 3.5–5.25 wraps, respectively, for 16 self-thigh applications and 4.0 and 3–4.75 wraps, respectively, for 16 nonself-thigh applications). Arms received 4 to 7 wraps (median and range: 5.25 and 4.0–7.0 wraps, respectively, for 16 self-arm applications and 5.5 and 4.0–7.0 wraps, respectively, for 16 nonself-arm applications).

Ease of Application and Discomfort

The CAT, SWAT-T, and pneumatic applications were mostly rated as Easy except for the SWAT-T 1-handed applications (Table IV). The CAT applications involved greater discomfort than the SWAT-T or pneumatic applications and were the only ones with Severe ratings (Table V).

Gender Differences

No tourniquet pressure or occlusion differences were observed between male and female recipients and appliers. No differences in ease of application were apparent. No differences in discomfort were apparent for CAT applications or pneumatic tourniquet applications, but a trend toward greater discomfort was noted for female recipients with the SWAT-T (male SWAT-T discomfort: 8 None, 7 Little, 9 Moderate, 0 Severe; female SWAT-T discomfort: 4 None, 17 Little, 19 Moderate, 0 Severe; $p = 0.07$).

Muscle Tension

Muscle relaxation resulted in lower pressures under each tourniquet than muscle tension. This was most appreciable with the CAT. Compared to the completion pressures, intentional muscle relaxation resulted in pressure decreases (CAT thigh 16 mm Hg, arm 27 mm Hg; SWAT-T thigh 2 mm Hg, arm 4 mm Hg; pneumatic arm 6 mm Hg). Intentional muscle tensing resulted in pressure increases over the completion

TABLE IV. Ease of Application

Tourniquet	2- or 1-Handed Application	Easy	Challenging	Difficult
CAT	2-Handed	34	14	0
CAT	1-Handed	10	5	1
SWAT-T	2-Handed	43	5	0
SWAT-T*	1-Handed	2	11	3
Pneumatic	2-Handed	64	0	0

*$p < 0.0001$ SWAT-T 1-handed versus all 2-handed and CAT 1-handed application.

TABLE V. Discomfort

Tourniquet	None	Little	Moderate	Severe
CAT*	1	20	32	11
SWAT-T	12	24	28	0
Pneumatic	41	22	1	0

*$p < 0.0001$ CAT versus SWAT-T and pneumatic applications.

pressures (CAT thigh 25 mm Hg, arm 44 mm Hg; SWAT-T thigh 2 mm Hg, arm 6 mm Hg; pneumatic arm 20 mm Hg). For the relaxation/tension cycles, relaxation pressures were always lower (tensed—preceding relaxed pressure in order of occurrence: CAT thigh 41, 58, and 34 mm Hg; CAT arm 70, 57, and 64 mm Hg; SWAT-T thigh 4, 6, and 13 mm Hg; SWAT-T arm 11, 9, and 16 mm Hg; Pneumatic arm 14, 15, and 23 mm Hg; $p < 0.01$ CAT versus SWAT-T and Pneumatic).

DISCUSSION

Consistent with our two main hypotheses, arterial occlusion pressures were lower with the wider SWAT-T and pneumatic blood pressure cuffs than with the CAT, and completion pressures with the SWAT-T and CAT were higher than arterial occlusion pressures. The finding of many occlusion and completion pressures over 500 mm Hg with the CAT was unexpected and concerning. Also unexpected was the finding of rather large pressure drops over 1 minute with the CAT. Not surprising was the finding that pneumatic blood pressure cuffs inflated to occlusion pressure did not maintain occlusion well over time.

Considering the pneumatic blood pressure cuff observations first, we would state that the use of a pneumatic blood pressure cuff as other than a transient tourniquet is not ideal. If a pneumatic blood pressure cuff is used as a hemorrhage-stopping tourniquet, it should be inflated beyond the occlusion pressure; consideration should be given to clamping the tubing, and it will need to be closely monitored. This makes the pneumatic blood pressure cuff not ideal as an on-scene or tactical tourniquet. The observed pressure drops with the blood pressure cuffs would not be expected with the pneumatic EMT since the EMT was actually designed to maintain occluding pressure for sustained use. In fact, military experience with the pneumatic EMT supports its effectiveness so long as it remains undamaged.[4]

The observed CAT occlusion pressures greater than 500 mm Hg were unexpected for two reasons. First, the predicted occlusion pressure for the CAT even for a user with a thigh circumference at the 99th percentile for a U.S. male soldier (71.46 cm) is only 380 mm Hg.[4,9,17] Second, reports involving military use of the CAT indicate that arterially occlusive tourniquet use is saving lives with a low incidence of tourniquet-related neuropathy.[2,4–6,18–20] Since the CAT is the most frequently used tourniquet by U.S. military personnel,[4,5] this would be inferential data suggesting military CAT use pressures are generally in the "safe" zone. The occlusion and completion pressures observed with the CAT are concerning, especially for tourniquet durations beyond 2 hours.[10]

In addition to the unexpectedly high completion pressures encountered with the CAT, we also observed a significant number of pulse return occlusion failures over the 1-minute observation period. The data shown in Figures 3 and 4 indicate that these pulse return occlusion failures would not be easily predicted by completion pressures, especially for thigh applications. Considering the number of completion and 1 minute pressures over 300 mm Hg among the CAT thigh occlusion failures, adding a second tourniquet[1,4] would definitely appear to be the preferred choice when available rather than simply tightening the already applied CAT.

We believe the large pressure decreases observed with the CAT between completion and 1 minute played an important role in CAT pulse return occlusion failures. The follow-up muscle tension effects on tourniquet pressures experiment supports a decrease in muscle tension under the CAT as the probable cause for the pressure loss. Decreases in underlying muscle tension could easily occur in a field situation and might be expected to have a similar adverse effect on field arterial occlusion effectiveness (retightening of tourniquets applied in a military setting has been reported as frequent[5]). Unlike air loss from a pneumatic tourniquet system, however, a muscle relaxation effect should have a finite limit and might be amenable to a single adjustment. The pressure loss data does indicate a need to recheck and potentially tighten an applied CAT within a short time after application (or add a second CAT if one is available and space allows[1,4]).

As with the CAT and the pneumatic blood pressure cuffs, SWAT-T occlusion pressures were higher than predicted. A few of the SWAT-T occlusion pressures and many of the SWAT-T completion pressures were over 300 mm Hg, but no SWAT-T pressures over 500 mm Hg were observed. The lower occlusion and completion pressures generated with the SWAT-T probably explain the lower discomfort ratings measured with the SWAT-T despite greater occlusion effectiveness at 1 minute. The lower pressures might also be expected to carry a lower risk for tourniquet induced nerve damage. Nerve damage, however, is related to pressure gradients, not just the average pressure.

The SWAT-T also had a lower rate of pulse return occlusion failures than the CAT. Furthermore, the data shown in Figures 3 and 4 suggest that only a small amount of additional pressure would have been needed to avoid the pulse return occlusion failures that did occur and that the resulting completion pressures could easily have been effective even if below 300 mm Hg.

The follow-up muscle tension effects on tourniquet pressures experiments showed considerably smaller pressure decreases under the elastic SWAT-T in response to muscle relaxation than under the nonelastic CAT. Presumably the smaller pressure drop in response to muscle relaxation played a role in the much lower rate of pulse return occlusion failures with the SWAT-T than was observed with the CAT. Any occurrence of occlusion failures, however, indicates a need to recheck and potentially tighten any applied SWAT-T within a short time after application as well.

The discordance between the observed and the predicted occlusion pressures indicates a need for actual pressure measurements with any tourniquet design. The equation for the predicted pressures[4] was derived from work with pneumatic cuffs with the measured pressure being that within the cuff rather than under the cuff.[9] One reason for our higher observed pressures, therefore, would be our measurement of pressure under each tourniquet (our observed pressures from under the adult pneumatic blood pressure cuffs were higher than the observed pressures within the adult pneumatic blood pressure cuffs 157 of 163 times). Another reason would be that pneumatic cuffs do not create the same tissue pressure profiles as straps (CAT) and elastic bands (SWAT-T).[21–23] Since predicted occlusion pressures were consistently lower than observed occlusion pressures, which were consistently lower than observed completion pressures, the use of predicted pressures to suggest tourniquet safety should be used with considerable caution.

Besides considering occlusion effectiveness and occlusion pressures, tourniquets for emergency and tactical use need to be relatively easy to apply.[4] The ratings of users suggest that both the CAT and SWAT-T meet this criteria. However, an easy to use rating and proper application are not one and the same.[16] Our research group found that it was difficult to adequately tighten the strap of the CAT prior to twisting the stick when using the two-handed strap routing configuration (pre-windlass pressures highest for one-handed self-arm application). We also found that without explicit, one-on-one, hands on training, many of the appliers given the full CAT instructions sheet and the CAT instructions PowerPoint did not differentiate between the one-handed strap configuration and the two-handed strap configuration (different routing through the friction buckle is called for by the manufacturer for the two different configurations). This matches well with the statement by Kragh et al[4] concerning military users that "During training, most appliers in training and care actually put the band in the one-handed routing inadvertently even when doing the two-handed application until corrected unless specifically forewarned." Consistent with our difficulties tightening the strap after routing it through the friction buckle, the discussion section of the Taylor et al[24] article with poor CAT thigh performance details the very sort of tightening problem that Kragh et al[4] describe as an application technique failure sometimes encountered with field users.

This study had several limitations. First, conditions favoring ease of measurement were used. Second, audible Doppler feedback was substituted for visual bleeding feedback. Third, the range of subject limb circumferences did not include the top end for U.S. soldiers.[17] Fourth, the neonatal #1 blood pressure cuff-based measurement system only provided information about pressure under a portion of each tourniquet. Fifth, the measurement system did not provide tourniquet edge pressure gradient information. And sixth, the tourniquets were only on uninjured volunteers and only for 1 minute; so only inferences can be made concerning the possible long-term clinical consequences of the observations.

CONCLUSIONS

This study had several important findings. First, occlusion pressures with each type of tourniquet were considerably greater than predicted. Second, standard blood pressure cuffs are likely to require considerable attention if used as field tourniquets. Third, occlusion and completion pressures were much lower and in a safer range with the wider SWAT-T than with the CAT. Fourth, many CAT applications that reached occlusion lost occlusion by 1 minute, probably related in most cases to pressure drops caused by muscle relaxation. Fifth, pre-windlass twisting pressures of the secured CAT band did not have a consistent relationship with the number of twists needed to reach occlusion.

We support the idea that the best tourniquets for field or tactical use are tourniquets designed for that setting. We also suggest that the SWAT-T offers some significant advantages over the windlass design CAT and should be among the tourniquets considered for field or tactical use.

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