

Different Width and Tightening System Emergency Tourniquets on Distal Limb Segments

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ABSTRACT

Background: Tourniquets are used on distal limb segments. We examined calf and forearm use of four thigh-effective, commercial tourniquets with different widths and tightening systems: 3.8cm windlass Combat Application Tourniquet® (CAT, combattourniquet.com) and Special Operations Forces® Tactical Tourniquet-Wide (SOFTT-W, www.tacmedsolutions.com), 3.8cm ratchet Ratcheting Medical Tourniquet™-Pediatric (RMT-P, www.ratcheting-buckles.com), and 10.4cm elastic Stretch-Wrap-And-Tuck Tourniquet® (SWATT, www.swattourniquet.com). **Methods:** From Doppler-indicated occlusion, windlass completion was the next securing opportunity; ratchet completion was one additional tooth advance; elastic completion was end tucked under a wrap. **Results:** All applications on the 16 recipients achieved occlusion. Circumferences were calf 38.1 ± 2.5 cm and forearm 25.1 ± 3.0 cm ($p < .0001$, t-test, mean \pm SD). Pressures at Occlusion, Completion, and 120-seconds after Completion differed within each design ($p < .05$, one-way ANOVA; calf: CAT 382 ± 100 , 510 ± 108 , 424 ± 92 mmHg; SOFTT-W 381 ± 81 , 457 ± 103 , 407 ± 88 mmHg; RMT-P 295 ± 35 , 350 ± 38 , 301 ± 30 mmHg; SWATT 212 ± 46 , 294 ± 59 , 287 ± 57 mmHg; forearm: CAT 301 ± 100 , 352 ± 112 , 310 ± 98 mmHg; SOFTT-W 321 ± 70 , 397 ± 102 , 346 ± 91 mmHg; RMT-P 237 ± 48 , 284 ± 60 , 256 ± 51 mmHg; SWATT 181 ± 34 , 308 ± 70 , 302 ± 70 mmHg). Comparing designs, pressures at each event differed ($p < .05$, one-way ANOVA), and the elastic design had the least pressure decrease over time ($p < .05$, one-way ANOVA). Occlusion losses differed among designs on the calf ($p < .05$, χ^2 ; calf: CAT 1, SOFTT-W 5, RMT-P 1, SWATT 0; forearm: CAT 0, SOFTT-W 1, RMT-P 2, SWATT 0). **Conclusions:** All four designs can be effective on distal limb segments, the SWATT doing so with the lowest pressures and least pressure losses over time. The pressure change from Occlusion to Completion varies by tourniquet tightening system and can involve a pressure decrease with the windlass tightening systems. Pressure losses occur in as little as 120 seconds following Completion and so can loss of Occlusion. This is especially true for nonelastic strap tourniquet designs.

KEYWORDS: *tourniquet; hemorrhage control; first aid; emergency treatment*

Introduction

Effective emergency tourniquets stop arterial blood flow out of the systemic circulation^{1,2} and have lifesaving roles in emergency care.²⁻⁵ The pressures required for effectiveness have a relationship with the circumference of the underlying limb and the width over which the pressure is applied.⁶⁻⁸ In general, smaller circumference locations and wider designs are expected to be associated with lower tourniquet-applied pressures at arterial occlusion than would be the case for larger circumference locations or narrower designs.⁶ Additionally, because higher pressures are associated with increased morbidity,^{9,10} emergency tourniquets that stop arterial blood flow at lower pressures are considered desirable.¹

The thigh is generally the largest-circumference limb segment and is expected to require the highest tourniquet pressures to reach and maintain arterial occlusion. The US military, therefore, has considered the thigh the key limb segment when evaluating the potential effectiveness of tourniquet designs.¹ The thigh, however, is not the only limb segment on which tourniquets are used.^{2,5,11}

The purpose of this study was to examine the distal limb segment use of four thigh-effective, commercial, emergency tourniquet designs with different widths and tightening systems. The hypotheses were as follows: (1) all of the tourniquets could occlude calf and forearm arterial blood flow; (2) tourniquet width would be associated with arterial occlusion pressures at each limb location independent of tourniquet tightening systems; and (3) the change in pressure from arterial occlusion to tourniquet application completion would vary by tightening system.

Methods

The Drake University institutional review board approved this prospective study. The Ratcheting Medical Tourniquet™-Pediatric (RMT-P; m2® Inc., www.ratcheting-buckles.com), the Combat Application Tourniquet® (CAT; Composite Resources, Inc., combattourniquet.com), and the Stretch-Wrap-And-Tuck Tourniquet® (SWATT; TEMS Solutions LLC, www.swattourniquet.com) were donated. The SOF® Tactical Tourniquet-Wide (SOFTT-W; Tactical

Medical Solutions Inc., www.tacmedsolutions.com) was purchased.

Tourniquets

The four tourniquets of different widths and tightening systems were the 3.8cm-wide windlass CAT and SOFTT-W; the 3.8cm-wide ratchet RMT-P; and the 10.4cm-wide elastic SWATT. The CAT, SOFTT-W, and RMT-P are each composed of a nonelastic fabric strap, friction buckle, tightening system, and mechanism for securing the tightening system for application completion (Figure 1A-C). The SWATT is composed solely of an elastic strap (Figure 1D).

The CAT has a 3.8cm-wide strap covered with hook-and-loop and connected on one end to a 9.3cm-long plastic base plate (Figure 1A). Inside the strap covered with hook-and-loop is another strap, 2.5cm wide, that runs from the friction buckle across the base plate, through a slot in the windlass, and then through the entire length of the hook-and-loop covered outer strap. The CAT friction buckle is plastic and has two slits with rough edges that grip. The CAT can be secured around the limb by using a single slit of the friction buckle combined with adherence of the hook-and-loop,^{12,13} which was done in this study, or by using both slits of the friction buckle with or without use of the hook-and-loop. Following tightening by windlass turning, the CAT windlass is secured by placement of one end within the windlass securing clip. The CAT had one discomfort-reducing modification made by the authors: the bare hook surface of the hook-and-loop on the skin side of the windlass securing clip was covered.

The SOFTT-W has a 3.8cm-wide strap connected on one end to a 17.4cm-long stiff webbing base and to a metal clip that connects to the friction buckle (Figure 1B). The 3.8cm-wide strap runs from the connection on the stiff webbing base, through a slot in the windlass (around which the strap is also connected), and then through a 7.3cm-long double portion of stiff webbing (part of the 17.4cm-long base). The SOFTT-W friction buckle is metal and has a center sliding portion that secures the correctly routed strap around the limb. After tightening by windlass turning, the SOFTT-W windlass is secured by placement of one end within the windlass-securing triangle.

The RMT-P has a 3.8cm-wide strap connected on one end to a friction buckle (Figure 1C). The 3.8cm-wide strap has a 1.9cm-wide by 10.0cm-long, plastic, toothed ladder riveted to it near the friction buckle and a 3.0cm-wide ratcheting buckle riveted to it at the other end of the ladder. The ladder material of the RMT-P is more flexible than that of other RMT models and is designed with a much lower tooth-load failure rating. The RMT-P friction buckle is composed of two overlapping,

4.0cm-diameter metal rings with a rough, friction-enhancing coating to secure the correctly routed strap around the limb. Throughout tightening by advancing the ratcheting buckle along the teeth of the ladder, the RMT-P ratcheting buckle is self-securing by ladder-tooth engagement of its internal pawl.

The SWATT is a 10.4cm-wide rubberlike strap (Figure 1D). The first wrap of the SWATT around the limb is secured by the friction of the following wrap. The SWATT is tightened by user stretching of the strap and by elastic recoil of the strap. Tightness increases with each wrap. During the last wrap, the end of the strap is tucked under a previous wrap to secure the tight tourniquet.

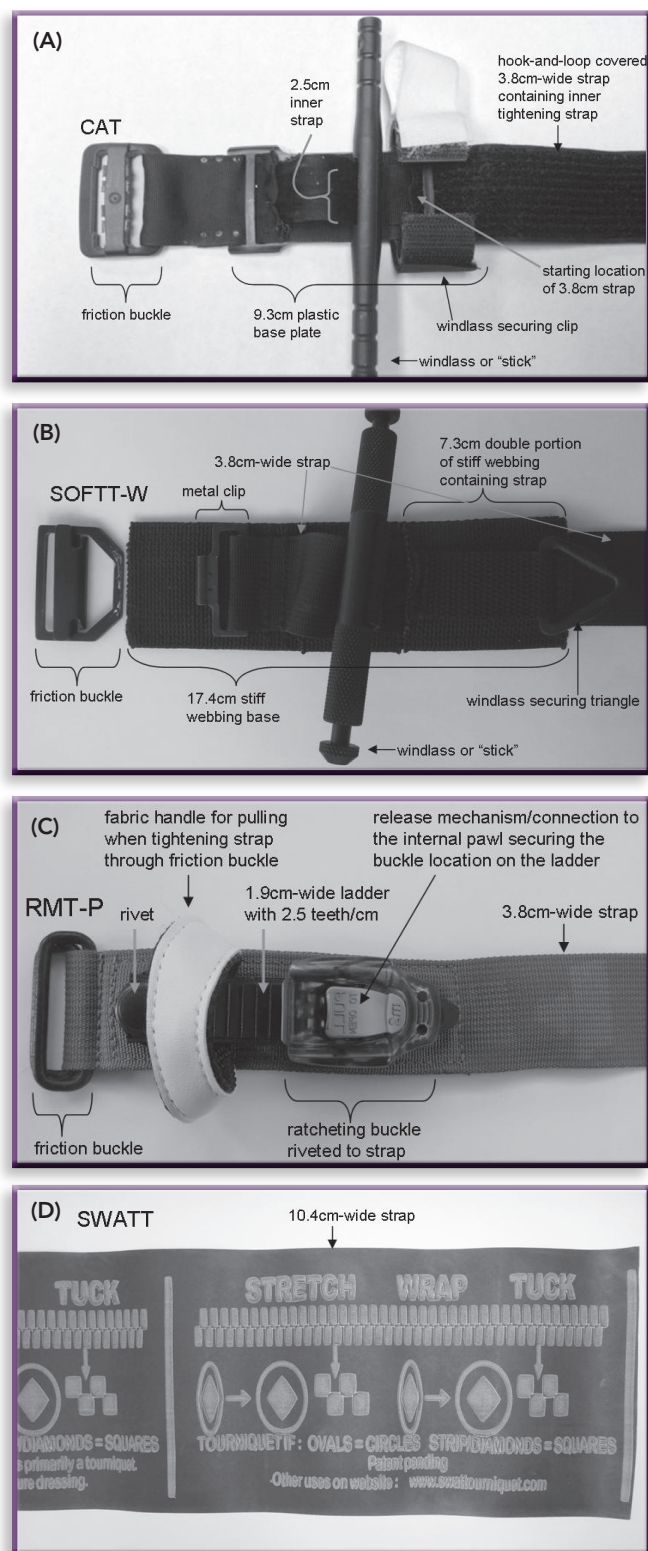
Pressure Measurements

Skin surface-applied pressures under the tourniquets were measured using two size #1 neonatal blood pressure cuffs (2.2cm × 6.5cm bladder, single tube). Each cuff was inflated to 10–15mmHg above atmospheric pressure, with the resulting pressure used as a baseline. The air-filled cuffs were taped to the tourniquets. On the CAT and SOFTT-W, one cuff was taped under the base; the second was taped under the strap alone at the same distance from the first cuff as was the case with the RMT-P. On the RMT-P, one cuff was taped under the strap beneath the ladder at the ladder attachment point to the strap; the second was taped under the strap alone just beyond the ratcheting buckle attachment point to the strap. On the SWATT, one cuff was taped near the starting end of the strap; the second was taped under the strap at the same distance from the first cuff as was the case with the RMT-P.

The cuffs were connected to a gas pressure sensor system (Vernier Gas Pressure Sensor, Vernier LabPro interface, and Logger Pro Software; Vernier Software and Technology, www.vernier.com). Pressures were continuously displayed graphically with numeric values displayed every second. Each tourniquet application's data were saved as complete, combined graphic and numeric data, with markers placed on the graph at each time point for pressure comparisons at the following events: strap secured around limb (Friction), arterial occlusion (Occlusion), and completion of application (Completion).

After data collection was complete, a decision was made to only use the pressure data from under the second cuff because the differing base portions of the two windlass tourniquets and the ladder-covered portion of the RMT-P provided differing amounts of expansion-constraint on the first cuff. Experiments showed that differences in cuff expansion-constraint clearly affected the pressure measurement from the cuff (less cuff expansion-constraint resulted in lower cuff pressures [data not shown]). Because the nonbase, nonladder portions of the tourniquets offered the most complete and consistent

Figure 1 (A) *Combat Application Tourniquet® (CAT; Composite Resources, Inc., combattourniquet.com).* (B) *Special Operations Forces Tactical Tourniquet-Wide (SOFTT-W; Tactical Medical Solutions Inc., www.tacmedsolutions.com)* (C) *Pediatric Ratcheting Medical Tourniquet (RMT-P; m2® Inc., www.ratchetingbuckles.com).* (D) *Stretch-Wrap-And-Tuck Tourniquet® (SWATT; TEMS Solutions LLC, www.swatttourniquet.com).*



expansion-constraint of the cuffs, only the pressure data from the cuffs under those portions of the tourniquets were used for analyses.

Friction Pressure

For the tourniquets with friction buckles, Friction Pressure was taken when the three following criteria were met: the strap was pulled as tightly around the limb as the applier could manage, the strap was secured by the hook-and-loop (CAT) or the friction buckle (SOFTT-W and RMT-P), and the applier's hands were off the tourniquet.

Occlusion Pressure

Occlusion was defined as the loss and then continued absence of the relevant audible distal arterial Doppler pulse signal (Ultrasonic Doppler Flow Detector Model 811 with 9.5MHz adult flat probe; Parks Medical Electronics, www.parksmed.com). Occlusion Pressure was marked when this was detected.

With the windlass tourniquets, tightening occurred throughout windlass turning. The data marker for windlass-tourniquet Occlusion Pressure was placed at an applier-held windlass position after the absence of an audible pulse signal was detected.

With the RMT-P, tightening occurred tooth by tooth as the pawl of the self-securing ratcheting buckle was advanced. When using the RMT-P, the audible pulse signal had to remain absent with the ratcheting buckle returned to its rest position to place the data marker for Occlusion Pressure.

With the SWATT, tightening occurred throughout wrapping. The data marker for SWATT Occlusion Pressure was placed at an applier-held strap position after the absence of an audible pulse signal was detected.

Completion Pressure

Completion was defined as the tourniquet secured with the applier's hands not in contact with the tourniquet. For the windlass tourniquets, Completion Pressure was recorded when the windlass was in the windlass locking clip (CAT) or triangle (SOFTT-W) at the closest opportunity that would hold the windlass tighter than its location at Occlusion Pressure. For the RMT-P, Completion Pressure was recorded at one tooth advance past Occlusion Pressure. For the SWATT, Completion Pressure was recorded after the free end had been securely tucked under a previous wrap.

120-second Pressure

We defined 120-seconds as 120 seconds after the time point at which Completion Pressure was recorded. The 120-second Pressure was taken at this time point.

Windlass Turns

The first 90° rotation of either windlass placed the windlass parallel to the strap of its tourniquet and was counted as zero turns. Each 180° windlass rotation thereafter was counted as one turn. Windlass turns were used to indicate the extent of use of the windlass tightening system.

RMT-P Ladder Distance

The RMT-P had 10 exposed teeth at the beginning of each application. The number of teeth still exposed was counted at Completion. This number was subtracted from 10 to determine how many teeth the ratcheting buckle had been advanced. The number of teeth advanced was used to indicate the extent of use of the ratchet tightening system.

SWATT Wraps

Each 360° wrap of the SWATT was counted as one wrap. The number of wraps was counted to the nearest one-quarter wrap at Completion. The number of wraps was used to indicate the extent of use of the elastic tightening system.

Subjects

Tourniquet recipients and appliers were volunteers and were paired. Recipient inclusion criteria were participation in a previous tourniquet study or participation in the related research course, ability to lie down and remain relaxed for 50 minutes, and age 18 years or older. Recipient exclusion criteria were self-reported blood clotting or circulation irregularities, implants in relevant locations, systolic blood pressure higher than 140mmHg, pain syndromes, or peripheral neuropathies.

The applier inclusion criterion was participation in the related research course. There were no applier exclusion criteria. Appliers were allowed unlimited training access to all tourniquets, printed instructions from the manufacturers, and instructional videos. Practice sessions were held, and verbal feedback was given to ensure correct applications. All protocol applications were supervised.

Protocol

1. Tourniquets were applied directly on skin.
2. Recipient information was collected (Table 1).
3. Recipients lay down throughout each application, with foam support and mid-range flexion of the relevant limb.
4. Recipients were directed to maintain the relevant limb in a completely relaxed state.
5. Paper draw determined whether the CAT or SOFTT-W was used first (randomized block).
6. One week later, the protocol was repeated, with paper draw determining whether the RMT-P or SWATT was used first (randomized block).
7. Each tourniquet was first applied to a calf around the measured and marked point one-quarter of the

Table 1 *Characteristics of Tourniquet Recipients*

Characteristic	Data
Sex, male/female, no.	8/8
Age, y	21, 19–54
Height, cm	173, 152–191
Weight, kg	70.5, 58.2–102.3
Systolic blood pressure, mmHg	108, 88–130
Circumferences of tourniquet locations, cm	
Calves	38.7, 31.7–42.5
Forearms	25.1, 19.5–30.2*

Data given as median, minimum–maximum unless otherwise indicated.

*Calf circumferences larger than forearm $p < .0001$.

distance from the posterior knee crease to the medial malleolus and then applied to a forearm around the measured and marked point one-quarter of the distance from the elbow crease to the wrist crease. Left limbs were used first.

8. In calf applications of 3.8cm-wide tourniquets, the friction buckle was placed on the anterior aspect of the calf, with the strap pulled downward around the lateral aspect of the limb to tighten.
9. In forearm applications of 3.8cm-wide tourniquets, the friction buckle was placed on the anterolateral aspect of the forearm, with the strap pulled downward around the lateral aspect of the limb to tighten.
10. In calf and forearm applications of the SWATT, the first wrap was positioned so the cuffs under the tourniquet were in the same locations relative to the recipient's anatomy as was the case for the 3.8cm-wide tourniquets. The wrapping direction was down laterally and up medially on each limb.
11. The strap of each 3.8cm-wide tourniquet was pulled as tight as the applier could manage before Friction Pressure was data marked.
12. The tightening system was engaged to reach Occlusion and Completion, with Occlusion Pressures and Completion Pressures data marked.
13. At Completion, the number of 180° windlass turns, the number of unengaged teeth remaining, or the number of wraps was recorded.
14. Appliers rated the ease of application as Easy, Challenging, or Difficult.
15. Recipients rated discomfort as None, Little, Moderate, or Severe.
16. The tourniquet was left in place for 120 seconds following Completion and then released and removed.
17. Any comments relating to the application were recorded.

Statistical Analysis

Numeric pressure data were organized in Microsoft® Office Excel 2003 (Microsoft Corp., www.microsoft.com). Pressure data were analyzed using a paired t-test,

one-way analysis of variance (ANOVA) with the Tukey multiple comparison test, one-way repeated measures ANOVA with Tukey multiple comparison test, linear regression, and the test for differences between variances of two independent samples.¹⁴ Contingency tables (ease, discomfort, occlusion loss) were analyzed using a chi-square test. Graphing and statistical analyses were performed using GraphPad Prism version 5.02 for Windows (GraphPad Software Inc., www.graphpad.com). Medians are shown along with minimums and maximums. Statistical significance was set at $p \leq .05$. All p values $< .10$ are reported.

Results

Tourniquets were applied to eight men and eight women. Six male and nine female undergraduate students were applicers (one female applicer was paired with two recipients). Recipient characteristics are shown in Table 1.

Friction Pressure

Friction Pressure depends on applicer technique and strength, and influences the extent of tightening system use needed to reach Occlusion. Previous work indicates that Friction Pressures of at least 150mmHg are desirable for achieving thigh Occlusion with only one CAT windlass turn,¹⁵ thereby minimizing CAT tourniquet deformation.¹⁶ Friction Pressures for each tourniquet application are shown in Figure 2 along with a dotted 150mmHg-threshold line.

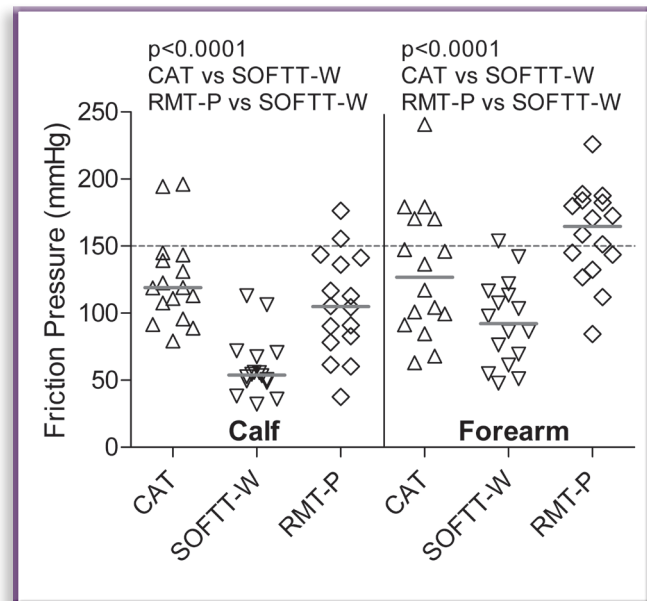
For a given tourniquet, applicers tended to achieve higher Friction Pressures on the forearm than on the calf (forearm versus calf: CAT, $p = .60$; SOFTT-W, $p = .0001$; RMT-P, $p < .0001$). Even on the forearm, however, many of the Friction Pressures were not greater than or equal to 150mmHg.

One recipient-applicer pairing was different for the RMT-P versus the CAT and SOFTT-W, so only 15 data sets were used for determining the tourniquet frequency of highest and lowest Friction Pressures. For each applicer-recipient pair, the highest calf Friction Pressure was most frequently achieved with the CAT (10 of 15 application sets) and the highest forearm Friction Pressure was most frequently achieved with the RMT-P (11 of 15 application sets). The SOFTT-W most frequently had the lowest Friction Pressure for an applicer-recipient pair regardless of limb (24 of 30 application sets).

Occlusion Pressure

Every tourniquet application achieved Occlusion. Two forearm applications achieved Occlusion during strap pulling to Friction Pressure. Those two applications had the highest two Friction Pressures: one was with the CAT, the other was with the RMT-P.

Figure 2 Friction Pressures of tourniquets with friction buckles. Calf Friction Pressures were commonly lower than forearm Friction Pressures: CAT: $p = .60$; SOFTT-W: $p = .0001$; RMT-P: $p < .0001$. SOFTT-W applications most frequently had the lowest Friction Pressures.



Occlusion Pressure is affected by recipient blood pressure, limb circumference, and tourniquet width.^{6,7} Occlusion Pressures are shown organized by tourniquet in Figure 3. Despite having the same 3.8cm width, the recorded RMT-P Occlusion Pressures were lower than the CAT and SOFTT-W recorded Occlusion Pressures. The 10.4cm-wide SWATT had the lowest Occlusion Pressures.

To account for differences in limb circumference, the Occlusion Pressures are graphed in Figure 4 against the ratio of limb circumference divided by tourniquet width. Larger ratios were generally associated with higher Occlusion Pressures. The linear regression slopes and intercepts for each tourniquet are shown in the legend on Figure 4; the curve fits were not high.

Completion Pressure

The Completion Pressures are shown in Figure 5A. The Completion Pressures were the starting pressures for completed tourniquet applications. As such, the Completion Pressures represent the pressures at which the applicers stop increasing the tourniquet applied pressures; ideally, therefore, the Completion Pressures should be as high as or higher than the Occlusion Pressures. Two CAT calf and three CAT forearm Completion Pressures were lower than their respective Occlusion Pressures. Five SOFTT-W calf and one SOFTT-W forearm Completion Pressures were lower than their respective Occlusion Pressures. No RMT-P and no SWATT Completion Pressures were lower than their respective Occlusion Pressures.

Figure 3 Occlusion Pressures of all four tourniquets. Of the 3.8cm-wide tourniquets, the RMT-P had the lowest Occlusion Pressures. The 10.4cm-wide SWATT had the lowest Occlusion Pressures of all of the tourniquets.

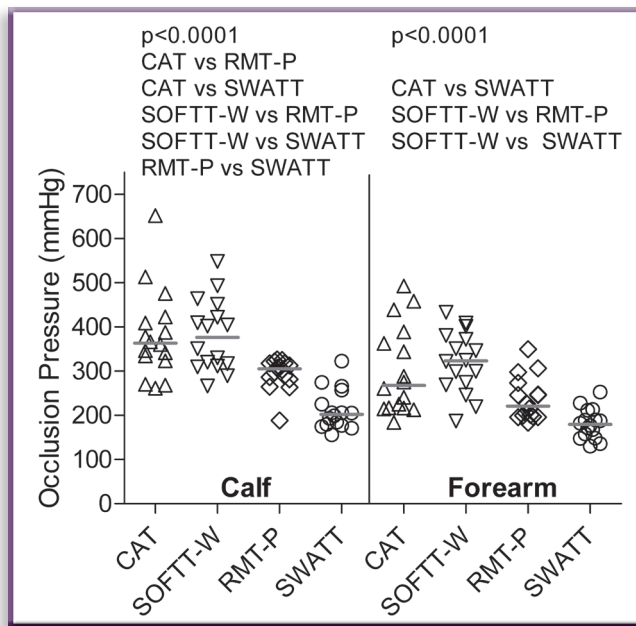
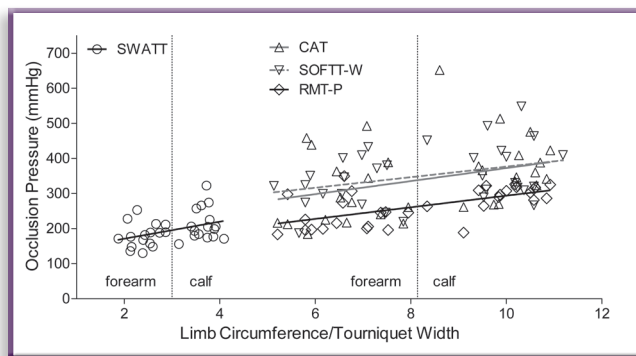
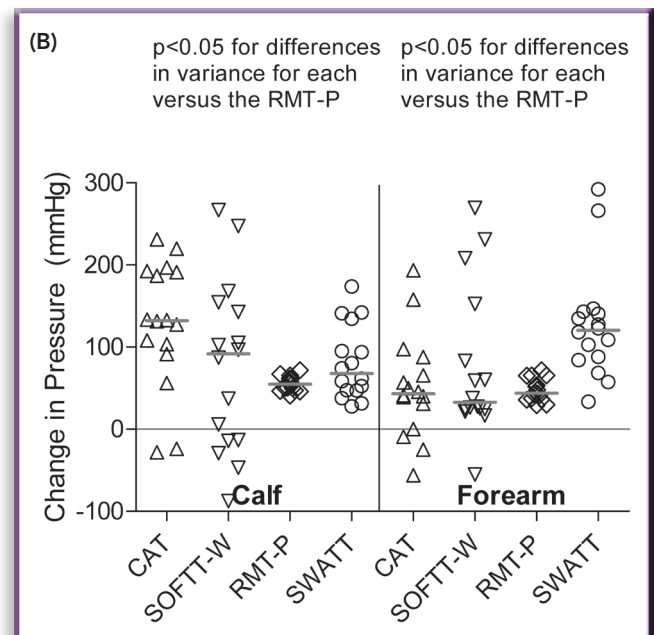
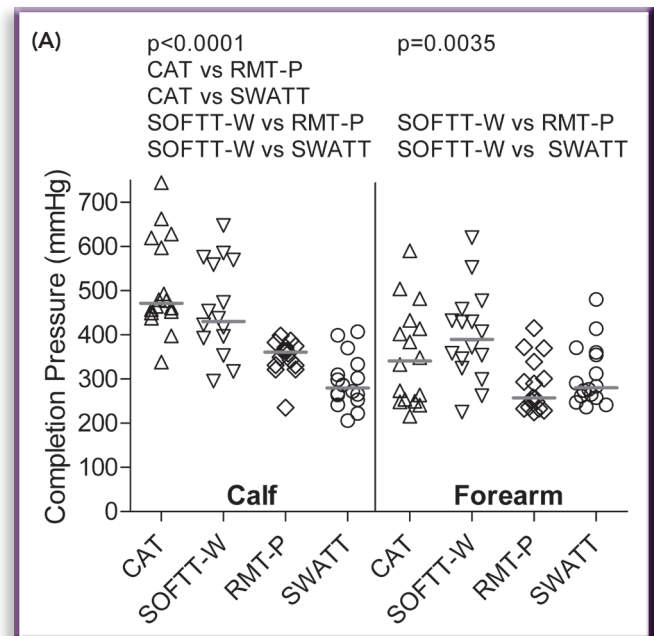


Figure 4 Occlusion Pressures versus the ratio of limb circumference divided by tourniquet width. The linear regression best fit slopes \pm standard errors, best fit intercepts \pm standard errors, and goodness of fit r^2 values for each tourniquet are as follows: CAT: 18.55 ± 9.63 , 187.1 ± 82.2 , $r^2 = 0.11$; SOFTT-W: 15.05 ± 7.37 , 226.2 ± 62.5 , $r^2 = 0.12$; RMT-P: 16.56 ± 3.84 , 128.3 ± 32.6 , $r^2 = 0.38$; and SWATT: 24.31 ± 10.40 , 122.6 ± 32.4 , $r^2 = 0.15$.



The pressure changes from Occlusion to Completion are shown in Figure 5B. The amount of change from Occlusion to Completion is affected by the tightening system. The increase from Occlusion to Completion was always a single tooth advance for the RMT-P, but the degrees of windlass turn to reach Completion varied across 180° for the CAT and the SOFTT-W. For the SWATT, the remaining length of the elastic strap needing to be wrapped and secured going from Occlusion to Completion was also more variable than the single tooth advance of the RMT-P. These windlass and elastic wrap differences from the ratcheting tightening system

Figure 5 (A) Completion Pressures of all four tourniquets. **(B)** Change in pressure from Occlusion to Completion. Negative values indicate decreases in pressure. The RMT-P had the most consistent increases from Occlusion to Completion.



resulted in more variation in the Occlusion to Completion pressure changes with the CAT, SOFTT-W, and SWATT than occurred with the RMT-P ($p < 0.05$ for each on calves and on forearms).

In addition to differences between the tourniquets, limb sizes influenced the pressure changes from Occlusion to Completion. With the CAT and RMT-P, the change from Occlusion to Completion was slightly less on the

smaller diameter forearms than on the calves (CAT, $p = .004$; RMT-P, $p = .07$). With the SWATT, an elastic tourniquet whose pressure increases with increasing wraps, the change from Occlusion to Completion was greater on the smaller diameter forearms than on the calves ($p = .03$).

120-Second Pressure

The 120-second Pressures are shown in Figure 6A. The 120-second Pressures are lower than the Completion Pressures for each tourniquet.

The pressure decreases from Completion to 120-seconds are shown in Figure 6B. Since the tourniquet recipients were directed to remain relaxed throughout the tourniquet applications, the observed pressure decreases are not likely to be a result of changes in recipient muscle tension. The 120-second pressure decreases were highest for the two windlass-tightened tourniquets but were substantial for all three nonelastic strap designs (combined median, 49mmHg; minimum–maximum: 7–153mmHg). The 120-second pressure decreases under the elastic strap SWATT were small (median, 5mmHg; minimum–maximum, 1–14mmHg). The number of 120-second Pressures below the Occlusion Pressures are shown in Table 2 for each tourniquet.

Reaching and Maintaining Occlusion

Although every tourniquet application reached Occlusion and was still occluding at Completion, several tourniquet applications did not maintain Occlusion over the 120 seconds from Completion to tourniquet removal. The number and distribution of applications with failures to maintain Occlusion are shown in Table 2. No failures to maintain Occlusion occurred with the elastic strap SWATT.

The Occlusion Pressures used in the comparisons in Table 2 were those of each tourniquet. An alternative for the 3.8cm-wide designs would be to use the RMT-P Occlusion Pressures (the lowest Occlusion Pressures of the 3.8cm-wide designs). All of the CAT, SOFTT-W, and RMT-P applications that failed to maintain Occlusion had 120-second Pressures greater than their respective RMT-P Occlusion Pressures.

Tightening-System Use

Tightening-system use at Completion is shown in Table 3. Fewer windlass turns were required for CAT applications than SOFTT-W applications. No SOFTT-W applications required fewer than two turns at Completion, but 10 CAT applications required only one turn at Completion. Calf applications required more windlass turns and more ladder-teeth use than did forearm applications with each tourniquet. The number of SWATT wraps, however, was less on the larger-diameter calves than on the forearms.

Ease of Application

Ease-of-application data are shown in Table 4. The SOFTT-W was the least easy to use. The main reason for the higher application-difficulty rating with the SOFTT-W was applicator difficulty securing the windlass in the windlass securing triangle (Figure 1B).

Recipient Discomfort

Recipient discomfort data are shown in Table 5. The SOFTT-W had the highest number of moderate and severe discomfort ratings. The RMT-P and SWATT had the lowest numbers of moderate and severe discomfort ratings.

Tourniquet Tightening Comments

Tightening the CAT windlass results in the formation of wrinkles progressing to small pleats in the 3.8cm-wide

Table 2 *Tourniquet Occlusion Maintenance*

Tourniquet	Location	Kept Occlusion	Lost Occlusion*	Times of Occlusion-Losses Following Completion (seconds)	Kept Occlusion, 120-second Pressure Less Than Occlusion Pressure	Lost Occlusion, 120-second Pressure Less Than Occlusion Pressure
CAT	Calf	15	1	120	3	1
SOFTT-W	Calf	11	5	14, 41, 46, 61, 92	3	4
RMT-P	Calf	15	1	95	2	1
SWATT	Calf	16	0	–	0	0
CAT	Forearm	16	0	–	7	0
SOFTT-W	Forearm	15	1	117	8	1
RMT-P	Forearm	14	2	65, 96	0	0
SWATT	Forearm	16	0	–	0	0

–, no data; CAT, Combat Application Tourniquet; RMT-P, Ratcheting Medical Tourniquet–Pediatric; SOFTT-W, SOF Tactical Tourniquet–Wide; SWATT, Stretch-Wrap-And-Tuck Tourniquet.

* $p = .028$ for combined calf and forearm differences in occlusion losses between tourniquets.

Table 3 Tourniquet Mechanical Advantage System Use at Completion*

Tourniquet	Location	Windlass Turns, Ladder Teeth, SWATT Wraps (median, minimum–maximum)
CAT	Calf	2, 1–4
SOFTT-W	Calf	3, 2–4
RMT-P	Calf	6.5, 4–9
SWATT	Calf	5.25, 3.5–6.25
CAT	Forearm	1, 0–3
SOFTT-W	Forearm	2, 2–3
RMT-P	Forearm	3, 0–5
SWATT	Forearm	6, 4.5–7.5

See Table 2 legend for expansion of abbreviations.

* $p = .0066$ for CAT calf versus SOFTT-W calf; $p = .0002$ for CAT forearm versus SOFTT-W forearm; $p = .0032$ for CAT calf versus forearm; $p = .015$ for SOFTT-W calf versus forearm; $p < .0001$ for RMT-P calf versus forearm; $p = .0008$ for SWATT calf versus forearm.

Table 4 Tourniquet Ease of Application*

Tourniquet	Location	Rating = Easy, No.	Rating = Challenging, No.	Rating = Difficult, No.
CAT	Calf	16	0	0
SOFTT-W	Calf	5	9	2
RMT-P	Calf	16	0	0
SWATT	Calf	12	4	0
CAT	Forearm	15	0	1
SOFTT-W	Forearm	10	2	4
RMT-P	Forearm	16	0	0
SWATT	Forearm	14	2	0

See Table 2 legend for expansion of abbreviations.

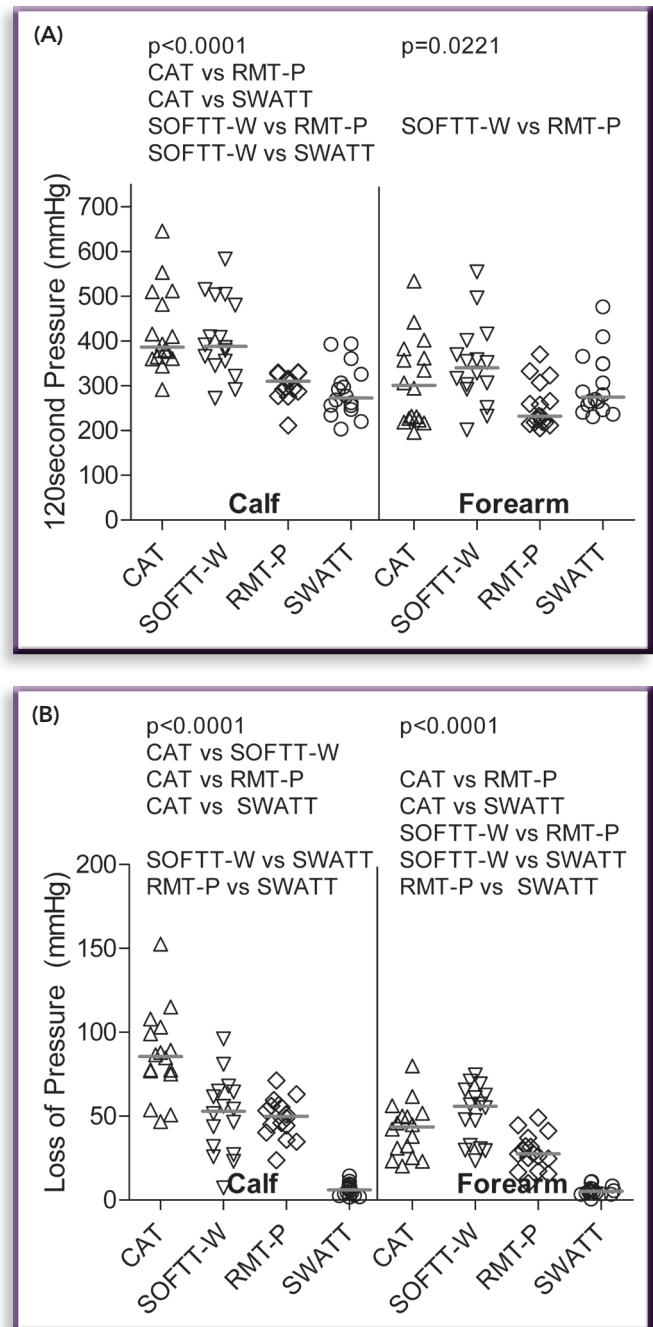
* $p < .0001$ for combined calf and forearm differences in ease of application between tourniquets.

hook-and-loop strap near the plastic base. The CAT base does not twist; the entire width of the base and of the hook-and-loop remains in contact with the limb during windlass tightening.

Tightening the SOFTT-W windlass results in some twisting of the webbing base of the SOFTT-W in addition to twisting of the 3.8cm-wide strap. Twisting of the base and of the strap results in a decreased limb-surface contact area against which the tourniquet pressure is exerted.

Tightening of the RMT-P via advancing the ratcheting buckle resulted in the formation of a few discrete bunches of the strap underneath the ladder. The bunches increased in size with increasing ratcheting buckle use. No portion of the RMT-P twists, so the entire 3.8cm width remains in contact with the limb during ratchet tightening.

Figure 6 (A) 120-second Pressures of all four tourniquets. (B) Loss of pressure from Completion to 120-seconds. All tourniquets had some pressure loss. The SWATT had the least pressure loss. The CAT and RMT-P had smaller pressure losses over 120 seconds on the forearms than on the calves ($p < .0001$ each).



Tourniquet Completion Comments

Securing the CAT windlass in its windlass securing clip is relatively easy. The backward travel of the windlass, once it is placed into the opening of the clip, can allow a Completion Pressure that is lower than the Occlusion Pressure.

Securing the SOFTT-W windlass in the windlass securing triangle can be difficult. Two applicers needed

Table 5 *Tourniquet Recipient Discomfort**

Tourniquet	Location	Rating = None, No.	Rating = Little, No.	Rating = Moderate, No.	Rating = Severe, No.
CAT	Calf	2	6	5	3
SOFTT-W	Calf	2	5	4	5
RMT-P	Calf	6	6	4	0
SWATT	Calf	2	10	3	1
CAT	Forearm	7	7	1	1
SOFTT-W	Forearm	4	5	7	0
RMT-P	Forearm	10	4	2	0
SWATT	Forearm	6	8	2	0

See Table 2 legend for expansion of abbreviations.

* $p = .024$ for combined calf and forearm differences in recipient discomfort between tourniquets.

assistance securing the SOFTT-W windlass. Although the windlass securing triangle of the SOFTT-W does not allow as much backward travel of the windlass as does the windlass securing clip of the CAT, SOFTT-W Completion Pressures can still result that are lower than Occlusion Pressures.

Discussion

The CAT, SOFTT-W, RMT-P, and SWATT can all stop arterial flow when used on the calf or forearm. The 10.4cm-wide, elastic strap SWATT stops arterial flow at the lowest pressures of the four tourniquets. Surprisingly, the limb- and recipient-matched Occlusion Pressure measurements with the three 3.8cm-wide, nonelastic strap tourniquets varied significantly from each other. Not surprisingly, the smaller-circumference forearms tended to have lower Occlusion Pressures than the larger-circumference calves. Also, the pressure change from Occlusion to Completion varies by tourniquet-tightening system.

Friction Buckle Design and Friction Pressure

Each of the 3.8cm-wide, nonelastic strap tourniquets had a different friction buckle design. The CAT friction buckle was single slit routed, rather than double slit routed, and, therefore, was used predominantly for strap direction change prior to strap securing with the hook-and-loop. This routing is approved in the Tactical Combat Casualty Care Guidelines¹³ as being effective, faster, and commonly used even in leg CAT applications.^{12,16} Despite single slit routing, applicators frequently did not reach Friction Pressures greater than 150mmHg, and, consequently, more windlass turns than would be ideal were frequently necessary.^{15,16}

Unlike the CAT, the straps of the SOFTT-W and RMT-P were composed of relatively smooth webbing. Both the SOFTT-W and RMT-P had metal friction buckles, but the buckle design of the SOFTT-W involved a moveable

metal crosspiece that clamped down on the strap during strap pulling and thereby impaired pulling the strap tight enough to achieve desirable Friction Pressures. In contrast, the slip-lock rings friction buckle design of the RMT-P allowed applicators to reach Friction Pressures as high as or higher than those with the single routed CAT.

The assistance of a second person would probably allow higher Friction Pressures to be reached with the single routed CAT and the RMT-P. Additionally, we believe working with applicators on a pulling-tight-around-the-limb technique rather than pulling outward from or tangential to the limb would probably also result in the achievement of higher Friction Pressures with the single routed CAT and the RMT-P. Because of the nature of the buckle design, we do not believe either intervention would be of substantial use for improving the SOFTT-W Friction Pressures.

Occlusion Pressure Detection

Occlusion Pressures varied among the 3.8cm-wide tourniquets. This could represent actual differences in the pressures required to reach Occlusion among the three 3.8cm-wide, nonelastic strap tourniquets. Alternately, this could represent difficulty detecting Occlusion as early as it occurred with each tourniquet. The RMT-P had the lowest Occlusion Pressures and the least scatter in those pressures. Both windlass designs had higher median Occlusion Pressure measurements with greater scatter than the RMT-P. The scatter with the windlass designs started with minimums similar to the RMT-P and then was distributed to higher maximums (Figure 3).

Differences in the tightening systems could account for the greater and predominantly upward scatter of the windlass tourniquets' Occlusion Pressures than those with the RMT-P. The ratcheting system of the RMT-P results in self-securing, discrete increases in pressure. A pause occurs following each tooth advance. The pause should allow the detection of Occlusion very close to

its occurrence and, therefore, accurate marking of Occlusion Pressure. With the windlass systems, appliers tended to rotate each windlass 180° at a time. Appliers often did not rotate the windlasses especially slowly, so the actual pressure at which Occlusion occurred could have been missed. A delay in Occlusion detection would result in recording incorrectly high Occlusion Pressures.

Evidence exists to support the possibility of delays in Occlusion detection with the windlass tourniquets. Occlusion Pressure data from under-the-strap portions of repeated thigh applications of the 3.8cm-wide CAT and Tactical RMT show differences in Occlusion Pressures between recipients but similar Occlusion Pressures for each tourniquet on each recipient.¹⁵ The majority of the tourniquet applications in the Slaven et al. study¹⁵ were done by one applier who was quite experienced with each tourniquet and the data points being investigated. This supports an expectation of similar distal limb-segment occlusion pressures for same-width nonelastic strap tourniquets independent of tightening system.

Occlusion Pressure Relationship With Limb Circumference and Tourniquet Width

A relationship has been shown to exist between tourniquet width and Occlusion Pressure, with wider tourniquets achieving Occlusion at lower pressures.^{6,7} With pneumatic tourniquets, a linear relationship has been suggested between the ratio of tourniquet width divided by limb circumference and Occlusion Pressure.^{6,17} An examination of distal limb segment circumferences and Occlusion Pressures (even of only RMT-Ps) along with previously reported thigh^{8,15} and arm⁸ 3.8cm-wide tourniquet strap Occlusion Pressures (Table 6) does not support the presence of a strong linear relationship between the ratio of tourniquet width divided by limb circumference and Occlusion Pressure with nonelastic, nonpneumatic strap tourniquets.

Completion Pressure, 120-second Pressure, and Occlusion Maintenance

The windlass designs had the highest Completion Pressures but, unlike the self-securing RMT-P and elastic SWATT, sometimes had Completion Pressures below their data-marked Occlusion Pressures. This seems undesirable and suggests an advantage to the self-securing RMT tightening system.

The windlass designs also had the greatest pressure losses between Completion and 120-seconds. All three nonelastic strap designs, however, had considerably larger pressure losses between Completion and 120-seconds than occurred with the SWATT. The fact that 10 failures to maintain arterial Occlusion for 120-seconds happened with the nonelastic strap designs while none happened with the elastic SWATT is probably related to the differing magnitude of pressure losses. We plan further investigation of the pressure-loss curves.

We believe pressure loss plays a mechanistic role in tourniquet failures to maintain Occlusion, but a simple pressure threshold relationship may not be present. Table 2 clearly indicates that some tourniquet applications with 120-second Pressures below their respective data-marked Occlusion Pressures were still without arterial pulses at 120-seconds.

Ease of Application

Clearly, appliers were able to successfully apply each tourniquet to each limb segment. In this study, we had assistants help hold the limb segments because we specifically requested recipients to remain muscle relaxed throughout the entire application and subsequent 120-second time periods. Because stretch is an important part of correct SWATT application, limb motion can easily be imparted during SWATT applications. Minimizing limb motion makes SWATT applications easier; so SWATT applications on a limb attached to a

Table 6 3.8cm-wide, Nonelastic Strap Tourniquet Occlusion Variables

Tourniquet	Location	Limb Circumference/Tourniquet Width (Median, Minimum–Maximum)	Occlusion Pressure (Median, Minimum – Maximum, mmHg)
RMT ¹	Thigh, n = 31	13.7, 10.4–17.1	348, 247–483
CAT ²	Thigh, n = 12	14.3, 10.9–16.3	319, 288–404
RMT ³	Thigh, n = 12	14.3, 10.9–16.3	326, 195–443
RMT ¹	Arm, n = 32	8.0, 5.7–9.9	235, 177–339
RMT-P	Calf, n = 16	10.1, 8.3–10.9	305, 189–327
RMT-P	Forearm, n = 16	6.6, 5.2–7.9	221, 184–350

See Table 2 legend for expansion of abbreviations.

¹Combined Tactical and Mass Casualty RMT strap pressure data from reference 8

²CAT strap pressure data from reference 15, each Occlusion Pressure value an average of 7 measurements on each recipient, same 12 recipients as RMT in next table row

³Tactical RMT strap pressure data from reference 15, each Occlusion Pressure value an average of 6 measurements on each recipient, same 12 recipients as CAT in previous table row.

body are likely to be easier than SWATT applications to an isolated limb model. Application of the three non-elastic tourniquets does not impart much limb motion, so use of an isolated limb model versus a limb attached to a body would be less likely to affect the ease of application with those designs.

Recipient Discomfort

Our results in this and prior studies indicate that severe discomfort is not indicative of, nor necessary for, tourniquet effectiveness.^{7,8,15} We speculate that the degree of discomfort associated with an arterially effective tourniquet relates to the following: (1) design choices such as sharp corners; (2) Completion Pressures, which relate to tourniquet width and tightening system; and (3) the character and extent of skin bunching, which relate to tightening system design and Friction Pressure.¹⁵

Conclusions

The 3.8cm-wide nonelastic strap CAT, SOFTT-W, and RMT-P, and the 10.4cm-wide elastic strap SWATT can all stop distal limb arterial flow. As expected, the pressures involved were lowest for the SWATT. Considering the reported pneumatic tourniquet circumference and pressure relationship,⁶ the 3.8cm-wide strap tourniquets' calf and forearm Occlusion Pressures were not as low as expected compared to prior thigh and arm applications.^{7,8}

The under-tourniquet pressure change from Occlusion to Completion varies by tourniquet tightening system and can involve a pressure decrease with the windlass tightening systems. Additionally, significant under-tourniquet pressure losses occur in as little as 120 seconds following Completion, and so can loss of Occlusion. This is especially true for nonelastic strap tourniquet designs.

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