Significant Pressure Loss Occurs Under Tourniquets Within Minutes of Application

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ABSTRACT

Background: Pressure decreases occur after tourniquet application, risking arterial occlusion loss. Our hypothesis was that the decreases could be mathematically described, allowing creation of evidence-based, tourniquet-reassessment-time recommendations. **Methods:** Four tourniquets with width (3.8cm, 3.8cm, 13.7cm, 10.4cm), elasticity (none, none, mixed elastic/nonelastic, elastic), and mechanical advantage differences (windlass, ratchet, inflation, recoil) were applied to 57.5cm-circumference 10% and 20% ballistic gels for 600 seconds and a 57.5cm-circumference thigh and 31.5cm-circumference arm for 300 seconds. Time 0 target completion-pressures were 262mmHg and 362mmHg. **Results:** Two-phase decay equations fit the pressure-loss curves. Tourniquet type, gel or limb composition, circumference, and completion-pressure affected the curves. Curves were clinically significant with the nonelastic Combat Application Tourniquet (C-A-T), nonelastic Ratcheting Medical Tourniquet (RMT), and mixed elastic/nonelastic blood pressure cuff (BPC), and much less with the elastic Stretch Wrap And Tuck-Tourniquet (SWATT). At both completion-pressures, pressure loss was faster on 10% than 20% gel, and even faster and greater on the thigh. The 362mmHg completion-pressure had the most pressure loss. Arm curves were different from thigh but still approached plateau pressure losses (maximal calculated losses at infinity) in similar times. With the 362mmHg completion-pressure, thigh curve plateaus were –68mmHg C-A-T, –62mmHg RMT, –34mmHg BPC, and –13mmHg SWATT. The losses would be within 5mmHg of plateau by 4.67 minutes C-A-T, 6.00 minutes RMT, 4.98 minutes BPC, and 6.40 minutes SWATT and within 1mmHg of plateau by 8.18 minutes C-A-T, 10.52 minutes RMT, 10.07 minutes BPC, and 17.68 minutes SWATT. Time-sequenced images did not show visual changes during the completion to 300 or 600 seconds pressure-drop interval. **Conclusion:** Proper initial tourniquet application does not guarantee maintenance of arterial occlusion. Tourniquet applications should be reassessed for arterial occlusion 5 or 10 minutes after application to be within 5mmHg or 1mmHg of maximal pressure loss. Elastic tourniquets have the least pressure loss.

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

Introduction

Effective emergency tourniquets stop blood loss by interrupting extremity arterial flow. Effectiveness is lost when the pressure exerted by the tourniquet becomes less than needed for arterial occlusion. This occurs on healthy individuals in the laboratory[1–3] and also may occur on injured individuals during field use.[4]

The consequences of preventing venous return without preventing outward arterial flow include ongoing blood loss, compartment syndrome, shock, and death.[5] Failure to achieve arterial occlusion occurs because the chosen tourniquet design is inadequate to the task, or because the user does not correctly apply an effective design. Failure to maintain arterial occlusion occurs because of tourniquet movement on the limb, increases in recipient arterial pressure, decreases in limb muscle tension,[1,2] and decreases in pressure applied by the tourniquet.[1–3]

Clinically significant decreases in tourniquet-applied pressure occur as quickly as 1 minute after completed tourniquet application.[1,2] Our study purpose was to characterize the pressure decreases occurring under several commercially available, effective emergency tourniquets. Our hypothesis was that the pressure decreases could be mathematically described, which should help provide evidence-based recommendations regarding reassessing tourniquet tightness and arterial occlusion after effective tourniquet application.

Methods

All human tourniquet use was on one of the authors (P.L.W.) and received institutional review board approval. The Combat Application Tourniquet® (C-A-T; Composite Resources Inc.; http://combattourniquet.com/), Tactical Ratcheting Medical Tourniquet™ (RMT; m2

Inc.; www.ratchetingbuckles.com), and Stretch Wrap And Tuck-Tourniquet® (SWATT; TEMS Solutions; www.swattourniquet.com) were donated. The extra-long-arm adult blood pressure cuff (Hokanson; www.deh-inc.com) was borrowed from the UnityPoint Health Iowa Methodist Medical Center Vascular Services Department.

Tourniquets

Four tourniquets of differing widths, elasticities, and tightening systems were used: 3.8cm-wide, nonelastic, windlass C-A-T (generation 6)[2,3]; 3.8cm-wide, nonelastic, ratcheting RMT (November 2014 manufacturing lot)[2,3]; 13.7cm-wide, elastic pneumatic bladder within nonelastic fabric, extra-long-arm adult blood pressure cuff; and 10.4cm-wide, elastic SWATT.[2,3] The nonelastic-strap tourniquets had friction buckles to secure the tightly pulled straps prior to engaging the windlass or ratchet tightening systems. The C-A-T also had hook-and-loop material on the strap. The blood pressure cuff had hook-and-loop material to secure the fabric strap prior to bladder inflation.

As TCCC approved,[6] the C-A-T strap was single routed through the friction buckle. The C-A-T had two discomfort-reducing modifications by the authors: the windlass-securing clip skin-side hook-and-loop was covered, and the base plate corners were taped.

Pressure Measurements

Tourniquet pressures were measured using one size #1 neonatal blood pressure cuff (2.2cm × 6.5cm bladder; single tube).[1–3,7] The baseline was atmospheric pressure. The cuff bladder was inflated 10–15mmHg above baseline. The cuff was taped under the strap at equivalent distances from the C-A-T base plate and RMT ratcheting buckle. On the SWATT and adult blood pressure cuff, the neonatal cuff was taped the same distance from the starting edge as on the RMT. The bladder was 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) with continuous graphic display and numeric values every second.[2,3]

Tourniquets, Compositions, Completion-Pressures, and Circumferences

Tourniquets were applied to 10% and 20% synthetic ballistic gel cylinders (Clear Ballistics; clearballistics.com) and a live, relaxed human thigh and upper arm. Each gel cylinder had a central, longitudinal, 1 inch diameter stainless steel tube. Gel and limb circumferences were 57.5cm for the cylinders and thigh location, and 31.5cm for the arm. The use of two different compositions of ballistic gel and a human thigh, all of the same circumference at the location of tourniquet placement, allowed circumference to be held constant while tourniquet type, material composition, and completion-pressure were varied.

At time 0, each tourniquet was applied three times at two target completion-pressures (262mmHg and 362mmHg) on each gel and the thigh. On the arm, the C-A-T, RMT, and SWATT were used, and the SWATT only at 262mmHg. Each application was in place on ballistic gel for 600 seconds (10 minutes) and the thigh and arm for 300 seconds (5 minutes). Arm tourniquet use was limited because the arm was primarily used to allow investigation of limb circumference effects, and, even with the 3.8cm-wide C-A-T and RMT, both completion-pressures were higher than necessary for arterial occlusion with the involved arm.

The use of two target completion-pressures allowed the effects of variations in completion-pressure to be explored. The completion-pressure targets were a pressure already known to be arterially occlusive for the narrowest two tourniquets (C-A-T and RMT) on the involved thigh and a pressure 100mmHg lower. Thigh arterial occlusion with those two tourniquets was previously determined using Doppler ultrasound monitoring of the distal pulse. Thigh and arm arterial occlusion monitoring during the experiments was via pulse oximetry, which is less sensitive for detecting the loss of tourniquet arterial occlusion (unpublished data).

Size and Shape Changes

Photographs containing each entire cylinder and the thigh distal and proximal to the tourniquet, including boundary lines drawn on the thigh distal and proximal to the tourniquet placement line, were taken at the following time points: no tourniquet; tourniquet placed without pressure applied; completed application; 10, 20, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, and 600 seconds (tourniquet off thigh); and 30 minutes (ballistic gel only). Pictures were analyzed for size and shape changes via the stack function and polygon traces using the Fiji version of ImageJ (fiji.sc/Fiji, downloaded August 2015).[8] At least 30 minutes passed between tourniquet applications.

Measurement System Constraint Experiments

To determine if inadequate bladder constraint could be responsible for decreasing pressures under the nonelastic tourniquets, a neonatal cuff was placed under the C-A-T and RMT in a bare condition or sewn within 1-inch polyester tubular webbing. Each bladder-condition tourniquet combination was applied three times to 20% ballistic gel (600 seconds each) and to the thigh (300 seconds each) at 362mmHg.

Statistical Analyses

Pressure data were organized in Microsoft® Office Excel 2003 (Microsoft Corp.; www.microsoft.com). Pressure changes per second since tourniquet-application-completion were calculated. Nonlinear regression was used to compare pressure changes per second between the conditions of different constraints, tourniquets, compositions, completion-pressures, and circumferences.

Graphing and statistical analyses were performed using GraphPad Prism version 5.02 for Windows (GraphPad Software Inc.; www.graphpad.com). Statistical significance was set at $p \leq .05$.

Results

Arterial Occlusion

Thigh C-A-T and RMT applications with 262mmHg completion-pressures did not maintain arterial occlusion. All other thigh and all arm tourniquet applications maintained arterial occlusion.

Completion-Pressures, Friction-Pressures, Mechanical Advantage Use

Table 1 shows completion-pressures achieved with each tourniquet application. Table 1 also shows C-A-T and RMT friction-pressures (i.e., the pressures exerted with the strap secured but the mechanical advantage system not yet engaged). Friction-pressure does not affect the pressure at which occlusion occurs but does affect mechanical advantage system use and thereby affects strap bunching, which affects tissue (or gel) under the tourniquet.[9]

Pressure-Loss Curves

Pressure losses occurred under each tourniquet (Figures 1 and 2). Pressure-loss curves for all C-A-T, RMT, and blood pressure cuff applications are well-described mathematically with two-phase decay equations:

$$y = \text{Plateau} + \text{SpanFast} \times e^{(-\text{Kfast} \times x)} + \text{SpanSlow} \times e^{(-\text{Kslow} \times x)}$$

This means each curve can be characterized as having a maximum pressure loss after infinite time defined as the plateau value, and the rate of pressure loss can be characterized as having a fast and slow half-life occurring concomitantly. In other words, the pressure (y) at any given time (x) is equal to the sum of the plateau (a negative number representing the total pressure loss at infinity) plus the amount of loss at time (x) from the fast process plus the amount of loss at time (x) from the slow process. The time (x) is multiplied by each rate constant (KFast and KSlow) to determine the negative exponent to which e (2.718, the base of the natural logarithm) is raised in each portion of the equation. SpanFast and SpanSlow represent the portions of the pressure loss from each half-life (SpanFast = ($y0$ – Plateau) × PercentFast × 0.01, SpanSlow = ($y0$ – Plateau) × (100 – PercentFast) × 0.01, PercentFast = the percentage of the span from $y0$ to Plateau accounted for by the faster decay rate). The larger the time (x), the smaller the positive values are for loss from the fast component and from the slow component; so the closer pressure (y) becomes to the plateau.

Pressure-loss curves for SWATT applications are also well-described with two-phase decay equations. However, curves from SWATT 20% ballistic gel and arm applications at 262mmHg had many combinations of parameter values that led to equally good curve fits (Table 2).

Pressure-loss curve equation parameters, goodness-of-fit values, and times to <5mmHg and <1mmHg from plateau are shown in Table 2. Complete equations are shown in Table 3. The values of greatest clinical interest in Table 2 are thigh and arm plateau pressures and times. Plateau pressures indicate pressure losses are greater with higher completion-pressures and least with the SWATT. The times for thigh and arm pressure losses to become within 5mmHg or 1mmHg of plateau suggest 5 or 10 minutes as a reasonable reassessment time.

Tourniquets, Compositions, Completion-Pressures, and Circumferences

Pressure-loss curves were highly affected by tourniquet design (Figures 1 and 2); considerably less and slower pressure loss occurred with the elastic SWATT. The C-A-T and RMT had statistically significantly different decay equations despite both using a 3.8cm-wide nonelastic strap. The blood pressure cuff, despite containing an elastic bladder, had pressure-loss curves more similar to C-A-T and RMT curves than to SWATT curves.

Pressure-loss curves for each tourniquet were affected by the composition of the material (10% gel, 20% gel, thigh) on which they were applied (Figures 1 and 2). Pressure-loss curves were also affected by completion-pressures (Figures 1 and 2). Plateau loss values (loss after an infinite time interval) were of greater absolute magnitude on 10% ballistic gel than 20% ballistic gel, and were of greater absolute magnitude with higher completion-pressures.

Thigh pressure-loss curves (Figure 1C and Figure 2C) did not match those of the 10% or 20% ballistic gel (Figure 1A and Figure 2A). On each gel, during at least the first 300 seconds, the blood pressure cuff curves tended to have the greatest absolute magnitude pressure losses (all pressure losses hereafter are discussed as absolute magnitude unless otherwise indicated). On the thigh, the blood pressure cuff curves had lesser pressure losses than did the C-A-T or RMT. The C-A-T and RMT also had much steeper pressure-loss curves through 60 seconds on the thigh than the gels. Additionally, the times for pressure losses to approach plateau were longer for applications on either gel than for applications on the thigh.

Table 1 *Completion-Pressures, Friction-Pressures, Mechanical Advantage System Use*

Tourniquet Application: Target Completion-Pressure, Gel or Limb, Tourniquet	Completion-Pressures (mmHg)	Friction-Pressures (mmHg)	Number of Windlass Turns or Ratchet Teeth Advances
262mmHg			
10% ballistic gel			
C-A-T	268, 265, 258	151, 158, 151	1,1,1
RMT	261	125	18
Blood pressure cuff	268, 269, 274	NA	NA
SWATT	263, 260, 263	NA	NA
20% ballistic gel			
C-A-T	274, 264, 259	88, 85, 97	1,1,1
RMT	258, 275, 260	126, 176, 162	9, 7, 7
Blood pressure cuff	276, 262, 254	NA	NA
SWATT	276, 269, 265	NA	NA
Human thigh			
C-A-T	272, 250, 287	100, 105, 108	1, 1, 1
RMT	253, 251, 263	82, 96, 96	8, 8, 9
Blood pressure cuff	271, 279, 276	NA	NA
SWATT	248, 268, 283	NA	NA
Human arm			
C-A-T	259, 253, 275	85, 84, 131	1, 1, 1
RMT	297, 250, 279	110, 95, 103	7, 5, 5
SWATT	255, 251, 262	NA	NA
362mmHg			
10% ballistic gel			
C-A-T	350, 368, 347	191, 218, 195	3, 3, 3
Blood pressure cuff	368, 369, 366	NA	NA
SWATT	387, 347, 357	NA	NA
20% ballistic gel			
C-A-T	361, 373, 355	172, 170, 156	2, 2, 2
RMT	356, 355, 354	175, 181, 193	15, 12, 12
Blood pressure cuff	362, 365, 361	NA	NA
SWATT	367, 369, 361	NA	NA
Human thigh			
C-A-T	413, 352, 402	151, 148, 157	1, 1, 1
RMT	328, 352, 345	80, 87, 87	11, 10, 11
Blood pressure cuff	366, 371, 370	NA	NA
SWATT	330, 365, 353	NA	NA
Human arm			
C-A-T	340, 335, 334	82, 84, 82	1, 1, 1
RMT	418, 353, 409	121, 119, 119	6, 6, 6

C-A-T, Combat Application Tourniquet; RMT, Ratcheting Medical Tourniquet; NA, not applicable; SWATT, Stretch Wrap And Tuck-Tourniquet.

In thigh C-A-T and RMT applications, higher completion-pressures resulted in faster pressure losses and more negative plateaus than occurred at lower completion-pressures. Despite greater losses at the higher completion-pressures, the final tourniquet pressures at infinity would still be higher than with the lower completion-pressures. To restate, the higher completion-pressure plateau pressures were not 100mmHg greater than the lower completion-pressure plateau pressures.

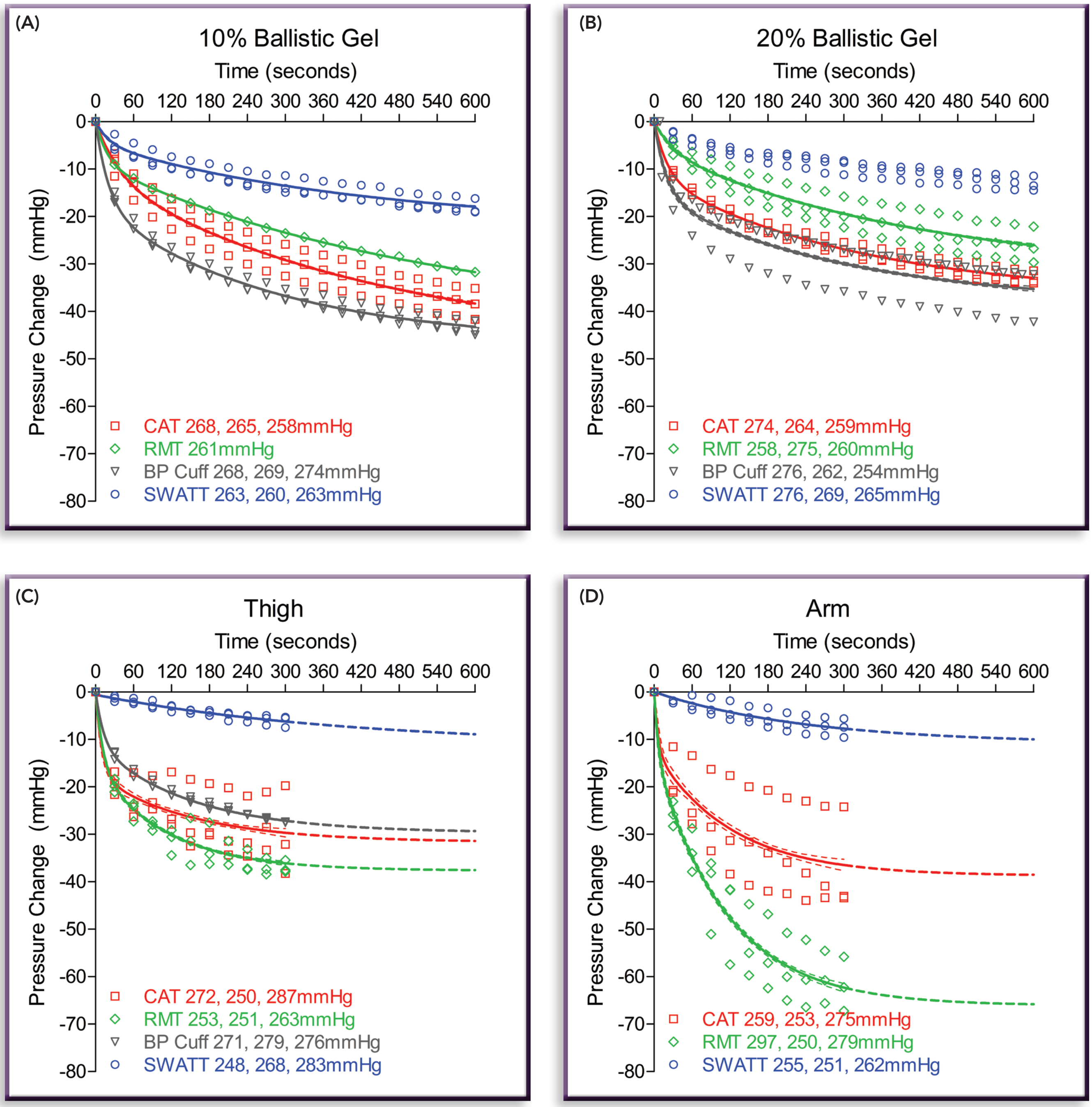
The lower completion-pressure C-A-T and RMT thigh applications had pulsatile pressure decay traces as a consequence of not maintaining occlusion. The pressure pulsations are not well shown with graphed data points at 30 second intervals (Figure 1C).

Similar to thigh applications, arm application pressure-loss curves (Figure 1D and Figure 2D) involved faster pressure losses and greater plateaus with the higher completion-pressures than the lower completion-pressures. The pressure-loss curves of the smaller circumference arm applications frequently involved more pressure loss than thigh applications.

Size and Shape Changes

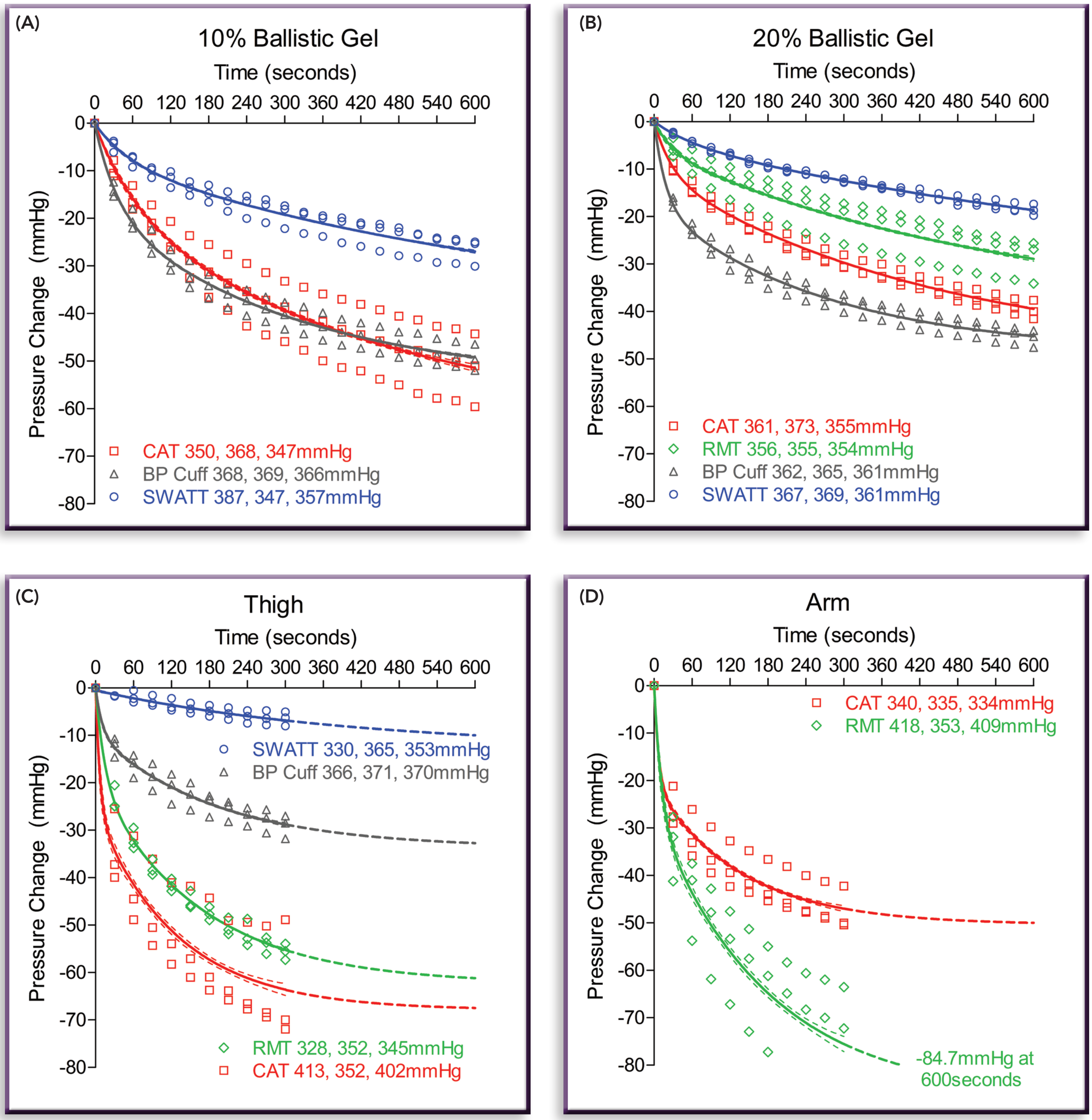
Size and shape changes occurred during tourniquet tightening to application-completion: the portion of ballistic gels and thigh directly under each tourniquet became smaller in diameter (Figures 3 and 4). Visible changes did not occur during the 300 or 600 seconds after application-completion. Upon tourniquet removal,

Figure 1 *Pressure-loss curves with tourniquet target completion-pressure of 262mmHg.*



In each panel, individual markers indicate data points at 30 second intervals for each tourniquet application. Lines show the two-phase decay curves for each tourniquet. The 95% confidence intervals for the two-phase decay curves are also present but are often so narrow they visually overlap the decay curve. The dashed 301 through 600 second line continuations for thigh and arm two-phase decay curves are calculated from their respective equations. The pressures shown in the legend are the actual completion-pressures with each application. **(A)** Pressure-loss curves on 10% ballistic gel for Combat Application Tourniquet (C-A-T), Ratcheting Medical Tourniquet (RMT), blood pressure (BP) cuff, and Stretch Wrap And Tuck-Tourniquet (SWATT). **(B)** Pressure-loss curves on 20% ballistic gel for C-A-T, RMT, blood pressure cuff, and SWATT. **(C)** Pressure-loss curves on thigh for C-A-T, RMT, blood pressure cuff, and SWATT. **(D)** Pressure-loss curves on arm for C-A-T, RMT, and SWATT.

Figure 2 *Pressure-loss curves with tourniquet target completion-pressure of 362mmHg.*



In each panel, individual markers indicate data points at 30 second intervals for each tourniquet application. Lines show the two-phase decay curves for each tourniquet. The 95% confidence intervals for the two-phase decay curves are also present but are often so narrow that they visually overlap the decay curve. The dashed 301 through 600 second line continuations for thigh and arm two-phase decay curves are calculated from their respective equations. The pressures shown in the legend are the actual completion-pressures with each application. **(A)** Pressure-loss curves on 10% ballistic gel for Combat Application Tourniquet (C-A-T), Ratcheting Medical Tourniquet (RMT), blood pressure (BP) cuff, and Stretch Wrap And Tuck-Tourniquet (SWATT). **(B)** Pressure-loss curves on 20% ballistic gel for C-A-T, RMT, blood pressure cuff, and SWATT. **(C)** Pressure-loss curves on thigh for C-A-T, RMT, blood pressure cuff, and SWATT. **(D)** Pressure-loss curves on arm for C-A-T and RMT.

Table 2 *Pressure-Loss Curve Information*

Tourniquet Application: Target Completion-Pressure, Gel or Limb, Tourniquet	Plateau (mmHg)	Fast Half-Life (sec)	Slow Half-Life (sec)	% Fast	Goodness-of-Fit R^2	Time to <5mmHg from Plateau (min:sec)	Time to <1mmHg from Plateau (min:sec)
262mmHg							
10% ballistic gel							
C-A-T	–48	26.6	315.9	23.8	0.92	15:09	27:22
RMT	–43	13.2	376.1	20.8	1.0*	17:22	31:55
Blood pressure cuff	–47	14.4	193.3	38.1	0.98	8:09	15:38
SWATT	–22	14.6	296.4	20.7	0.90	9:00	20:28
20% ballistic gel							
C-A-T	–37	14.6	224.9	31.5	0.97	8:47	17:29
RMT	–32	20.2	287.4	17.6	0.85	11:34	22:41
Blood pressure cuff	–38	14.6	213.1	41.1	0.70	7:45	16:00
SWATT	—†	44.2	—†	—†	0.89	—‡	—‡
Human thigh							
C-A-T	–32	7.3	106.1	55.4	0.49	2:40	6:46
RMT	–38	8.4	78.9	42.3	0.87	2:48	5:51
Blood pressure cuff	–30	8.9	104.8	37.6	0.99	3:19	7:22
SWATT	–11	0.4	281.7	5.1	0.87	5:09	16:07
Human arm							
C-A-T	–39	4.2	84.5	31.6	0.48	3:24	6:40
RMT	–66	4.7	78.7	19.6	0.86	4:29	7:32
SWATT	–11	—†	169.0	—†	0.68	3:15	5:06
362mmHg							
10% ballistic gel							
C-A-T	–64	44.7	308.8	25.2	0.87	16:45	28:42
Blood pressure cuff	–55	24.8	218.0	32.7	0.96	10:28	18:54
SWATT	–42	36.9	491.9	17.9	0.92	22:45	41:47
20% ballistic gel							
C-A-T	–50	19.1	309.1	21.5	0.98	15:16	27:14
RMT	–41	20.9	395.2	14.7	0.82	18:32	33:50
Blood pressure cuff	–49	12.3	190.0	36.3	0.97	8:21	15:42
SWATT	–34	42.3	608.8	11.5	0.99	26:10	49:45
Human thigh							
C-A-T	–68	4.9	91.1	38.4	0.71	4:40	8:11
RMT	–62	10.3	116.3	31.6	0.98	6:00	10:31
Blood pressure cuff	–34	7.1	131.2	28.3	0.90	4:59	10:04
SWATT	–13	0.7	291.4	4.0	0.78	6:24	17:41
Human arm							
C-A-T	–50	5.0	96.2	41.4	0.84	4:07	7:50
RMT	–87	7.9	124.2	30.8	0.77	7:26	12:14

—, no single value or no value (see footnotes † and ‡); C-A-T, Combat Application Tourniquet; RMT, Ratcheting Medical Tourniquet; SWATT, Stretch Wrap And Tuck-Tourniquet.
*RMT on 10% ballistic gel only had one trial.
†No single value because many combinations of parameter values led to equally good curve fits.
‡No value because there was no single plateau value.

the ballistic gels and thigh rebounded to some extent immediately and completely by 30 minutes.

Tourniquet Application Consequences after 300 and 600 Seconds

No ballistic gel tearing occurred with the blood pressure cuff. One SWATT application on the 10% gel had tearing. Gel tearing occurred with the C-A-T and RMT. The worst tearing occurred with the RMT on the 10% gel at the higher completion-pressure and was sufficient to preclude repeating that application combination. The RMT-associated gel tearing occurred at the edges of the deeply indenting strap bunches created by advancing the ratcheting buckle (see Table 1 for numbers of teeth advanced).

Ballistic gel tearing with the C-A-T was also worse on the 10% gel and at the higher completion-pressure than on the 20% gel or at the lower completion-pressure. The C-A-T-associated gel tearing occurred at the base plate and friction buckle edges.

No skin tearing occurred, and at no point was sufficient discomfort induced for the recipient to stop an application or have a tourniquet removed early. On the thigh,

Table 3 *Two-Phase Decay Equations for Each Tourniquet Application*

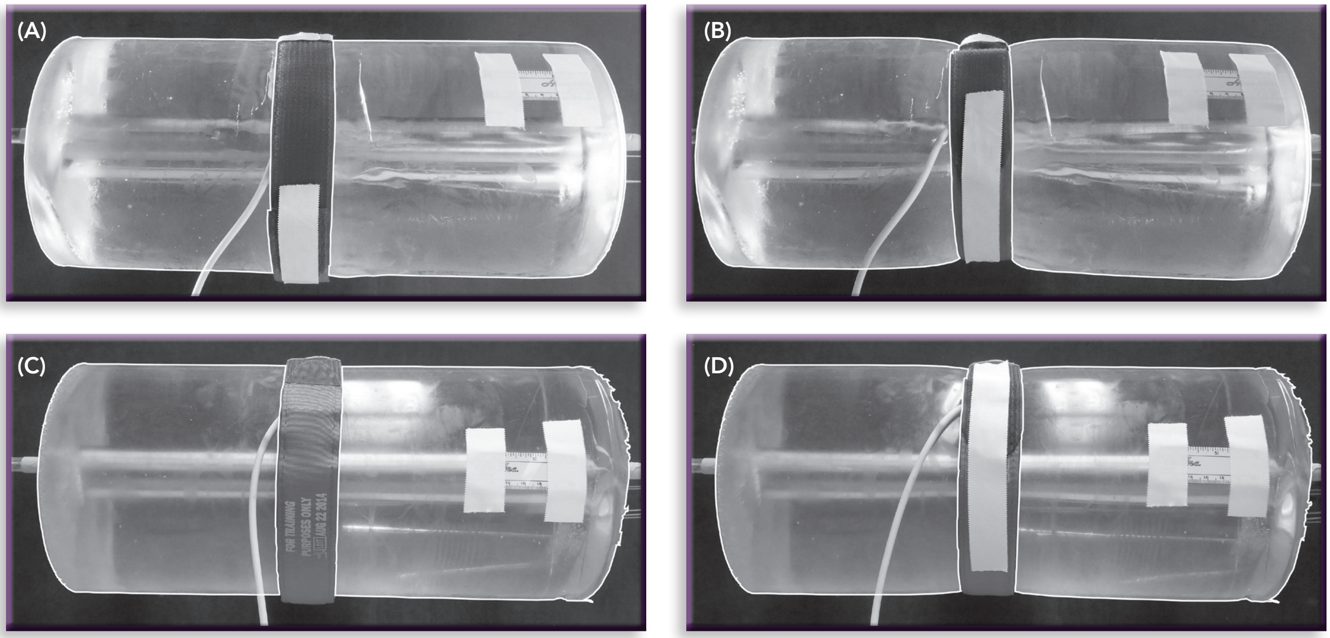
Tourniquet Application: Target Completion-Pressure, Gel or Limb, Tourniquet	Two-Phase Decay Equation* $y = \text{Plateau} + \text{SpanFast} \times e^{(-\text{KFast} \times x)} + \text{SpanSlow} \times e^{(-\text{KSlow} \times x)}$
262mmHg	
10% ballistic gel	
C-A-T	$y = -48.2 + 11.4 \times e^{(-0.02602 \times x)} + 36.7 \times e^{(-0.002195 \times x)}$
RMT	$y = -43.0 + 8.93 \times e^{(-0.05258 \times x)} + 34.1 \times e^{(-0.001843 \times x)}$
Blood pressure cuff	$y = -46.6 + 17.7 \times e^{(-0.04800 \times x)} + 28.9 \times e^{(-0.003585 \times x)}$
SWATT	$y = -22.3 + 4.61 \times e^{(-0.04758 \times x)} + 17.6 \times e^{(-0.002339 \times x)}$
20% ballistic gel	
C-A-T	$y = -36.9 + 11.6 \times e^{(-0.04735 \times x)} + 25.3 \times e^{(-0.003082 \times x)}$
RMT	$y = -32.3 + 5.69 \times e^{(-0.03433 \times x)} + 26.6 \times e^{(-0.002412 \times x)}$
Blood pressure cuff	$y = -38.5 + 15.8 \times e^{(-0.05111 \times x)} + 22.7 \times e^{(-0.003253 \times x)}$
SWATT	no equation†
Human thigh	
C-A-T	$y = -31.7 + 17.5 \times e^{(-0.09503 \times x)} + 14.1 \times e^{(-0.006532 \times x)}$
RMT	$y = -37.7 + 15.9 \times e^{(-0.08286 \times x)} + 21.7 \times e^{(-0.008788 \times x)}$
Blood pressure cuff	$y = -29.7 + 11.2 \times e^{(-0.07786 \times x)} + 18.5 \times e^{(-0.006611 \times x)}$
SWATT	$y = -11.4 + 0.581 \times e^{(-1.5000 \times x)} + 10.8 \times e^{(-0.002461 \times x)}$
Human arm	
C-A-T	$y = -38.7 + 12.2 \times e^{(-0.1659 \times x)} + 26.5 \times e^{(-0.008205 \times x)}$
RMT	$y = -66.1 + 13.0 \times e^{(-0.1468 \times x)} + 53.1 \times e^{(-0.008805 \times x)}$
SWATT	no equation†
362mmHg	
10% ballistic gel	
C-A-T	$y = -63.8 + 16.1 \times e^{(-0.01550 \times x)} + 47.7 \times e^{(-0.002245 \times x)}$
Blood pressure cuff	$y = -54.7 + 17.9 \times e^{(-0.02797 \times x)} + 36.8 \times e^{(-0.003179 \times x)}$
SWATT	$y = -41.7 + 7.46 \times e^{(-0.01879 \times x)} + 34.2 \times e^{(-0.001409 \times x)}$
20% ballistic gel	
C-A-T	$y = -49.6 + 10.6 \times e^{(-0.03634 \times x)} + 38.9 \times e^{(-0.002242 \times x)}$
RMT	$y = -41.2 + 6.05 \times e^{(-0.03318 \times x)} + 35.1 \times e^{(-0.001754 \times x)}$
Blood pressure cuff	$y = -48.7 + 17.7 \times e^{(-0.05404 \times x)} + 31.0 \times e^{(-0.003649 \times x)}$
SWATT	$y = -33.7 + 3.87 \times e^{(-0.01639 \times x)} + 29.8 \times e^{(-0.001138 \times x)}$
Human thigh	
C-A-T	$y = -67.9 + 26.1 \times e^{(-0.1425 \times x)} + 41.8 \times e^{(-0.007609 \times x)}$
RMT	$y = -62.4 + 19.7 \times e^{(-0.06742 \times x)} + 42.7 \times e^{(-0.005958 \times x)}$
Blood pressure cuff	$y = -33.7 + 9.55 \times e^{(-0.09724 \times x)} + 24.2 \times e^{(-0.005283 \times x)}$
SWATT	$y = -13.0 + 0.516 \times e^{(-1.009 \times x)} + 12.5 \times e^{(-0.002379 \times x)}$
Human arm	
C-A-T	$y = -50.4 + 20.9 \times e^{(-0.1399 \times x)} + 29.5 \times e^{(-0.007206 \times x)}$
RMT	$y = -86.8 + 26.7 \times e^{(-0.08723 \times x)} + 60.1 \times e^{(-0.005583 \times x)}$

C-A-T, Combat Application Tourniquet; RMT, Ratcheting Medical Tourniquet; SWATT, Stretch Wrap And Tuck-Tourniquet.
*Definitions of equation parameters:
y = pressure drop at time x.
$y0$ = y when $x = 0$ ($y0$ constrained to a value of 0 for the tourniquet applications).
x = time from completion ($x = 0$ at completed tourniquet application).
$e = 2.718$, the base of the natural logarithm.
Plateau = y at infinite times (the maximum pressure loss from completion to infinity).
SpanFast = ($y0$ − Plateau) × PercentFast × 0.01.
SpanSlow = ($y0$ − Plateau) × (100 − PercentFast) × 0.01.
KFast = the fast rate constant.
KSlow = the slow rate constant.
PercentFast = the percentage of the span from $y0$ to Plateau accounted for by the faster decay rate.
†No single value because many combinations of parameter values led to equally good curve fits.

temporary indentations occurred that visually matched those seen on the ballistic gels (Figure 5). The greatest indentation depths occurred under the strap bunches of the RMT created by advancing the ratcheting buckle (Table 1). These indentations were resolved within 30 minutes.

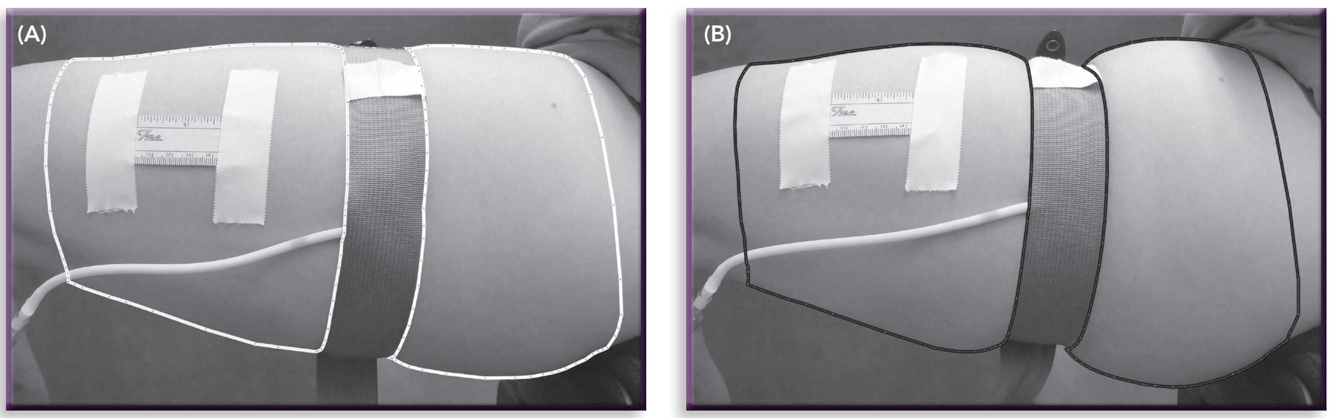
With same-day repeated thigh applications, some minor skin irritation and transient post-application tenderness occurred in the location of the C-A-T and RMT friction buckles. With arm applications, some minor skin bruising occurred with C-A-T and RMT applications, and some arm tingling occurred for several minutes post-C-A-T and RMT removals. Arm SWATT applications at 262mmHg also had post-removal arm tingling. Considering that 262mmHg was already much higher than needed for arm arterial occlusion with this tourniquet

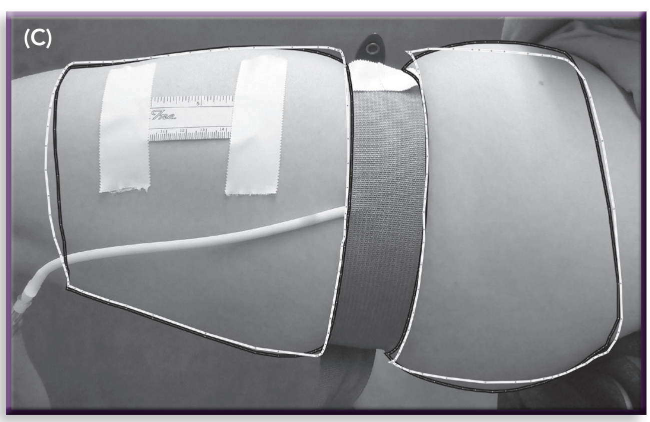
Figure 3 *Example polygon traces from 10% and 20% ballistic gel C-A-T application with target completion-pressure of 362mmHg.*



Polygon traces from tourniquet resting in place and tourniquet application-completion. **(A)** 10% ballistic gel with Combat Application Tourniquet (C-A-T) resting in place but not pulled tight and no mechanical advantage system engagement with white polygon traces. **(B)** 10% ballistic gel with C-A-T at application-completion with white polygon traces. **(C)** 20% ballistic gel with C-A-T resting in place but not pulled tight and no mechanical advantage system engagement with white polygon traces. **(D)** 20% ballistic gel with C-A-T at application-completion with white polygon traces.

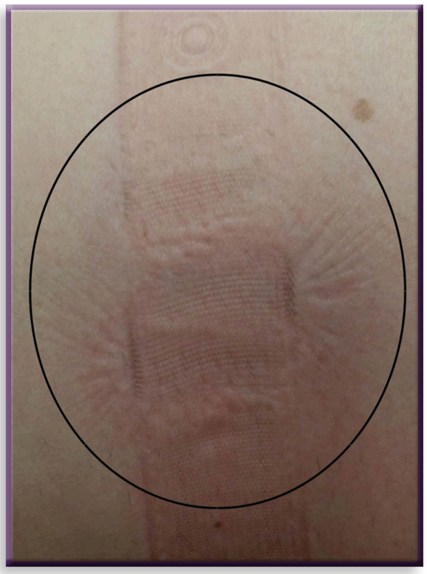
Figure 4 *Example polygon traces from thigh RMT application with target completion-pressure of 362mmHg.*



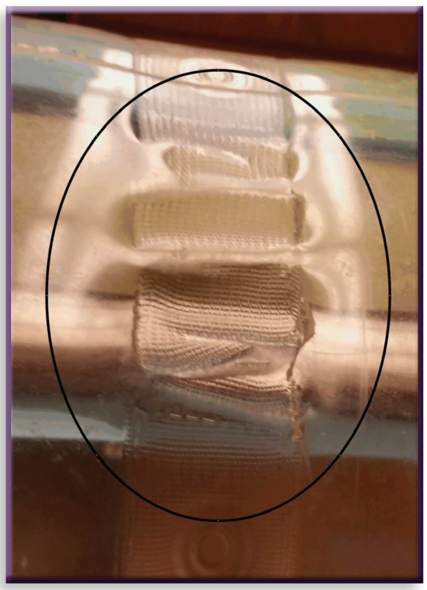


Polygon traces from tourniquet resting in place and tourniquet application-completion. **(A)** Thigh with Ratcheting Medical Tourniquet (RMT) resting in place but not pulled tight and no mechanical advantage system engagement with white polygon traces. **(B)** Thigh with RMT at application-completion with black polygon traces. **(C)** Thigh with RMT at application-completion with black polygon traces and inclusion of white polygon traces from tourniquet resting in place.

Figure 5 *Examples of temporary indentations on thigh and 20% ballistic gel immediately following Ratcheting Medical Tourniquet removal.*



(A) Thigh



(B) 20% ballistic gel

and considering the lesser amount of tissue protecting the nerve in the arm than in the thigh, 362mmHg applications of the SWATT to the arm were not done.

Measurement System Constraint Experiments

Use of the tubular webbing increased the bleb size created by the pressure measurement system underneath each tourniquet strap. Use of the tubular webbing resulted in statistically different two-phase decay equations ($p < .001$). The equation differences, however, were minor and insufficient for inadequate-bladder-constraint-against-expansion to be the cause of the observed tourniquet pressure-loss curves. The two-phase pressure decay curves with and without the tubular webbing are shown in Figure 6.

Discussion

Pressure losses unrelated to changes in muscle tension occur within minutes under completed applications of nonelastic tourniquets. Slower and smaller losses occur under completed applications of elastic tourniquets. Proper initial application does not guarantee arterial occlusion will be maintained. Given the opportunity, tourniquet applications should be assessed for continued arterial occlusion 5 or 10 minutes after application.

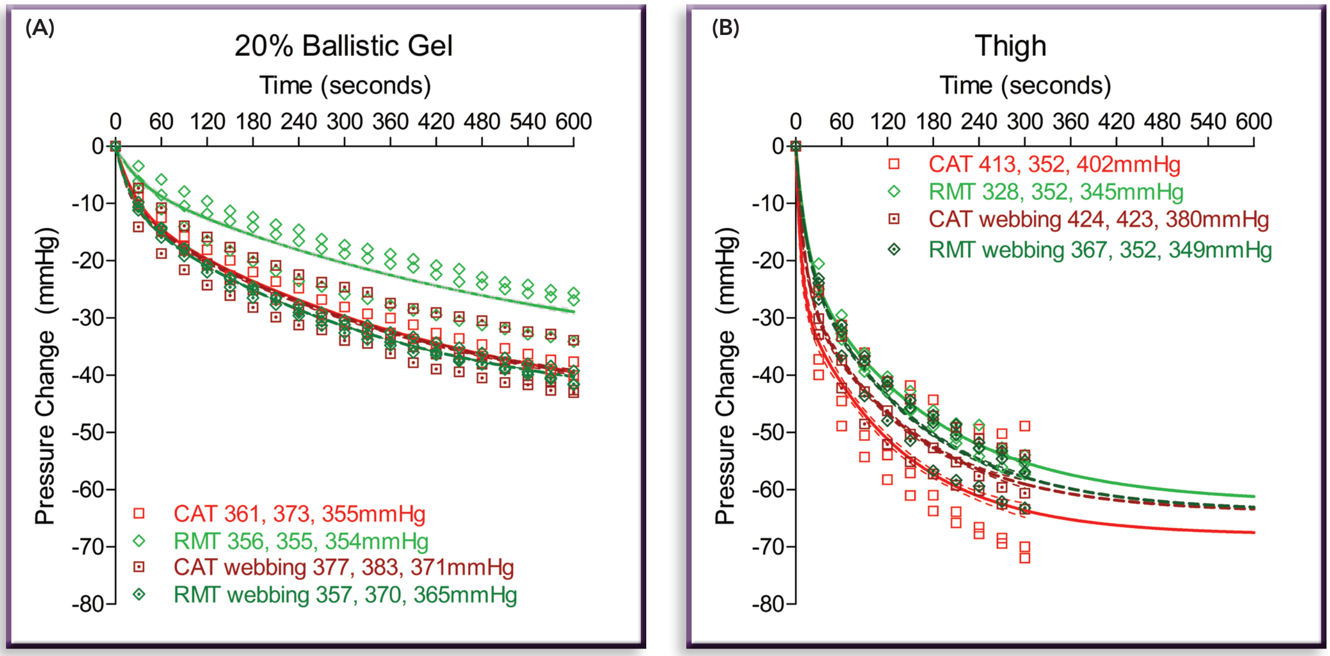
Field users are not likely to know the pressure exerted by an applied tourniquet or the tourniquet pressure needed to maintain limb arterial occlusion. Well-trained users know applying unlimited pressure is neither easy nor desirable. Therefore, even well-trained users may apply tourniquets that provide arterial occlusion at application-completion but will lose arterial occlusion within minutes, even in the absence of tourniquet movement, increases in recipient blood pressure, or decreases in limb muscle tension. This is especially true for nonelastic tourniquets.

The pressure losses are not from tourniquet fabric tearing or stretching. We propose tourniquet pressure losses result from tissue and, to a lesser extent, fluid movement away from pressure. During tourniquet application, a high-pressure zone is created. Fluid moves down pressure gradients; so fluid in blood vessels and interstitial spaces should move out from under a tourniquet. We believe such fluid movement occurs predominantly during, not after, application and does not account for pressure-loss curves following application-completion. Our reasoning is the ballistic gels do not have vascular or interstitial fluid and yet have pressure-loss curves bearing a resemblance to those of same-circumference, pressure-matched thigh tourniquet applications.

We did not detect changes in thigh or gel distortion from application-completion to tourniquet removal. Easily discernable limb and gel shape changes occurred under and to either side of each tourniquet during the process of application (Figures 4 and 3). Pressure increases during tourniquet application were 200–300 or more mmHg greater than pressure losses following application-completion. If shape changes occurred during the pressure losses after application-completion, they were too small for the sensitivity of our tools (two-dimensional images of approximately 95 pixels per centimeter).

Our data support the following as determinants of pressure-loss curve profiles: tourniquet type, material on which the tourniquet is applied, completion-pressure

Figure 6 *Pressure-loss curves with and without use of tubular webbing as additional bladder constraint.*



In each panel, individual markers indicate data points at 30 second intervals for each tourniquet application. Lines show the two-phase decay curves for each tourniquet. The 95% confidence intervals for the two-phase decay curves are also present but are so narrow that they visually overlap the decay curve. The 301 through 600 second line continuations for thigh two-phase decay curves are calculated from their respective equations. The pressures shown in the legend are the actual completion-pressures with each application. **(A)** Pressure-loss curves on 20% ballistic gel for Combat Application Tourniquet (C-A-T) and Ratcheting Medical Tourniquet (RMT) with and without tubular webbing as additional bladder constraint. The equation for the C-A-T with tubular webbing is $y = -48.6 + 10.7 \times e^{(-0.04578 \times x)} + 37.9 \times e^{(-0.002389 \times x)}$. The equation for the RMT with tubular webbing is $y = -46.6 + 10.3 \times e^{(-0.04539 \times x)} + 36.3 \times e^{(-0.002912 \times x)}$. **(B)** Pressure-loss curves on thigh for C-A-T and RMT with and without tubular webbing as additional bladder constraint. The equation for the C-A-T with tubular webbing is $y = -64.0 + 23.9 \times e^{(-0.08928 \times x)} + 40.1 \times e^{(-0.006954 \times x)}$. The equation for the RMT with tubular webbing is $y = -63.9 + 18.5 \times e^{(-0.07527 \times x)} + 45.4 \times e^{(-0.006729 \times x)}$.

of tourniquet application, and circumference around which the tourniquet is applied. From a modeling standpoint, the pressure-loss behavior of neither ballistic gel completely matched the pressure-loss behavior of the thigh. However, the less pliable 20% gel showed less pressure loss than the 10% gel, and both gels and the thigh showed faster and greater pressure losses with nonelastic tourniquets and higher completion-pressures. Circumference as a determinant of the pressure-loss-curve profile is supported by comparing the matched-completion-pressures thigh and arm curves.

The two completion-pressures used were both greater than needed for the SWATT or adult blood pressure cuff to occlude arterial flow through the recipient's thigh. Therefore, more appropriate completion-pressure applications of the SWATT or blood pressure cuff on the recipient's thigh would be expected to have slower and lesser pressure losses.

Both used completion-pressures were also higher than needed to occlude arterial flow through the recipient's arm with any of the tourniquets. Therefore, all would be expected to have slower and lesser pressure losses with more arm-appropriate completion-pressure applications.

One answer to the problem of pressure loss under nonelastic tourniquets within minutes after application would be to apply such tourniquets some amount tighter than needed for initial arterial occlusion. This is not a completely useful answer because "the amount tighter" is an amorphous amount influenced by tourniquet design, the pressure at which arterial occlusion occurs, and limb circumference. Even if the amount could be specified, most emergency tourniquets do not have pressure measuring systems. Additionally, the resolution of possible pressure increases varies with tourniquet mechanical advantage systems. Most windlass designs have securing options only at 180° increments (large pressure increases). The RMT has much finer pressure increase resolution, so a recommendation of a one or two tooth ratchet advancement beyond that needed to reach arterial occlusion may be wise. Of course, this presupposes the applier has sufficient attention available to determine just when arterial occlusion was reached.

An alternate answer to the pressure-loss problem is to include reassessment of the tourniqueted limb for arterial occlusion at a specified time shortly after application. The nonelastic, 3.8cm-wide C-A-T and RMT required the highest pressures to reach occlusion and had the fastest and greatest pressure losses. Within 5 minutes, both had pressure losses within 5mmHg of their loss plateaus and close to 1mmHg of their loss plateaus within 10 minutes on the thigh.

This study has the limitation of one tourniquet recipient. The advantages of one recipient are control of the tourniquet-important variables blood pressure, circumference, and tissue composition. Additionally, using one recipient allowed gel-circumference matching to the thigh, thigh-image matching across applications, and subjecting only one author to 300 second tourniquet durations and tourniquet pressures higher than needed for arterial occlusion. The gel cylinders' limitations are as follows: the gels do not compositionally match a human limb; the gel pressure decays are not identical to those of a thigh; and gels suffer some surface tearing that does not occur with skin. The cylinders' benefits were a precise and static experimental set-up, the ability to rule out free fluid movement, use of size-matched cylinders with different resistances to distortion in response to mechanical load (Poisson's ratios), extension of tourniquet durations, and repair with heat (270°F [132°C] melting temperature).

Conclusion

Even without tourniquet movement or limb muscle tension changes, pressure losses occur within minutes under tourniquets. These pressure losses are substantial with nonelastic tourniquets. Therefore, proper initial tourniquet application does not guarantee maintenance of arterial occlusion. Given the opportunity, tourniquet applications should be reassessed for continued arterial occlusion 5 or 10 minutes after application.

Disclosures

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