Lab Evaluation of Four Ukrainian-Manufactured Tourniquets

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ABSTRACT

Background: We evaluated arterial occlusiveness, 180° turns, pressures, reuse wear, and design aspects of four Ukrainian-manufactured tourniquets. **Methods:** Strengthened Individual Combat Hybrid Tourniquets (SICH), TQ DNIPRO GEN 2s (DNIPRO), PULS tourniquets (PULS), and Yellow&Blue tourniquets (Y&B) were each applied to left/right, mid-arm and mid-thigh, of 30 recipients, 100 seconds first-completion-to-release. Results were compared to concurrent study X8T-T2G (n=40). **Results:** All applications reached occlusion. Some thigh Y&B could not be secured: 1 never; three after additional turn. Twenty-six arms, 43 thighs needed an additional turn (median total turns arm 1.5 SICH, DNIPRO, PULS; 2.5 Y&B and thigh 2.5 SICH, DNIPRO; 2.0 PULS; 3.5 Y&B; p<.0001 others versus Y&B; X8T-T2G arm 0.7, thigh 1.5, p≤.0004 versus Ukrainian-manufactured). Ukrainian tourniquets pre-release, 39 arm and 83 thigh were >500mmHg (median range: occlusion arm 255–274mmHg, thigh 398–423mmHg; first completion arm 349–588mmHg, thigh 474–572mmHg; pre-release arm 350–638mmHg, thigh 517–583mmHg). No X8T-T2G >500mmHg (median pre-release arm 304mmHg, p<.002 versus SICH, DNIPRO, PULS and p=.522 versus Y&B; thigh 367mmHg, p<.0001 versus Ukrainian-manufactured). For per-turn pressure increases arm>thigh (p<.0001) and additional turns>turns-to-first-completion (p<.0001). Y&B concerns: stitching failures at rod-loop and limb-encircling strap connection; clip bending; potential slider-redirect-buckle-pieces loss, incorrect slider-redirect-buckle rethreading, and windlass-rod removal; and rod-securing inability. On 44.2–75.0cm-circumference thighs, hook-and-loop-strap-base-area-strap-securing mechanisms were not reached on 39% of applications. **Conclusions:** The SICH, DNIPRO, and PULS always reached completable arterial occlusion; Y&B did not and had design concerns. None became nonfunctional. Windlass-rod-tightening-system tourniquets routinely have higher-than-desirable completion pressures, which matters with long tourniquet times. Current hook-and-loop-limb-encircling straps are too short to engage base-area-strap-securing mechanisms on many adult thighs.

KEYWORDS: *tourniquet; hemorrhage; first aid; emergency; occlusion; pressure*

Introduction

Effective emergency-use limb tourniquets are first-aid items of life-saving importance in military conflicts.[1–3] To be effective, emergency-use limb tourniquets must allow achievement and hands-free maintenance of arterial occlusion when correctly applied. This requires designs that allow appliers to achieve tourniquet security with adequate circumferential pressure for arterial occlusion. Additionally, the designs should involve materials and construction techniques with sufficient robustness to withstand the forces to which they will be subjected during the initial application through all subsequent adjustments occuring from point-of-injury to definitive care.

We were contacted on 25 August 2023 by COL (Ret.) John F. Kragh, Jr. MD, regarding possible help evaluating emergency-use limb tourniquets of Ukrainian manufacture. We offered what we could do to help: assess tourniquet mid-arm and mid-thigh arterial occlusiveness according to distal audible Doppler signal; include tourniquet pressure information regarding how tightly appliers pull and secure the strap, pressure at occlusion, and pressure at completion with hands off; look for visually apparent damage with multiple uses; and identify difficulties encountered during use in the laboratory. Email conversations followed with the inclusion of Col (Ret.) Warren Dorlac, MD.

The study purpose was a laboratory evaluation of the following aspects of four Ukrainian-manufactured tourniquets: 1) achievement and maintenance of tourniquet-secured, arm and thigh arterial occlusion, 2) pressures involved in use, 3) amount of visible wear with reuses, and 4) general design considerations. The hypotheses were as follows: 1) all tourniquets would be able to achieve and maintain tourniquet-secured, arm and thigh arterial occlusion on all subjects, 2) occlusion pressures would be similar to reports for similar 3.8cm-wide nonelastic tourniquets with the same pressure-measuring system (higher for designs with other than full-width strap tightening), and 3) minimal visible wear would occur. Because we had an already planned, concurrent study with the X8T-T2G tourniquet (X8T, RCR Medical, McKinney, TX),[4] we also

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planned to compare Ukrainian-manufactured tourniquet pressures and tightening-system use obtained with the same appliers and most of the same recipients to those obtained with the X8T.

Methods

The Drake University Institutional Review Board approved this prospective study (#2023-24012), which took place August 2024 through April 2024.

Tourniquets

We had four of each tourniquet model: one for visual comparisons (never applied), one for practicing, one for right limbs, one for left limbs. We placed a little white mark on one end of each windlass rod as a possible aid in turn counting.

Four Ukrainian manufacturers provided tourniquets (Figure 1) to Col. (Ret.) Warren Dorlac, MD, who sent the tourniquets to us. The tourniquets are abbreviated as:

- SICH (Strengthened Individual Combat Hybrid Tourniquet; SICH Ukraine, LLC, Kyiv; Lot GS-III2023, manufactured 9/2023);
- DNIPRO (TQ DNIPRO GEN 2; TQ DNIPRO, Dnipro, Ukraine; Lot DNT2/23-17R 2023-09);
- PULS (PULS Tourniquet; PULS Tourniquet, Ternopil; G1D1023B, manufactured 10/20/2023); and
- Y&B (Yellow & Blue tourniquet; Yellow & Blue, Dnipro, Ukraine; Gen 5 manufactured 2/1/2023).

See reference 5 for tourniquet parts and references 6–9 for video tourniquet descriptions. The strap of the SICH was simple-threaded through the outer slot of the redirect. All use windlass-rod tightening systems. Windlass-rod rotations immediately affect SICH and Y&B strap pressure. Built-in slack in the DNIPRO and PULS internal strap cause a lack of pressure increase during the first 90° of rod rotation.

The X8Ts (Figure 1) were requested from and donated by the manufacturer (manufactured 04/25/2022). X8Ts have a self-securing-double-redirect strap/redirect system that cannot be unthreaded, a clip for securing around a trapped limb, and a self-securing tightening system with unidirectional dial rotation parallel to the limb surface (see Reference 10 for X8T video description). Dial rotation results in immediate, full-width circumferential strap shortening via shortening of a strap that is sewn around the secondary strap redirect and the clip of the primary strap redirect. Ten teeth advances (10 clicks) create 180° of dial rotation (equivalent to one 180° windlass-rod turn).

Appliers

Following practice, eight researchers were chosen as tourniquet appliers based on ability to frequently achieve pre-tightening-system-use pressures >100mmHg with the X8T. Availability determined which applier did each application.

Recipients

Volunteers were ≥18 years and had no known bleeding or clotting abnormalities, circulation problems, pain syndromes, peripheral neuropathies, connective tissue disorders, or conditions that would contraindicate tourniquet application (e.g., current forearm or thigh injuries).

Pressure Measurements

Pressures were measured using a No. 1 neonatal-blood-pressure-cuff bladder inflated to 18mmHg above atmospheric pressure (baseline), secured beneath the limb-encircling strap on the medial aspect of the limb, and connected to a Vernier Pressure Sensor 400, Vernier LabPro interface, and Logger Pro 3.16.2 Software (Vernier Science Education, Beaverton, OR).[11] Pressures were recorded every second. The system was not used in X8T applications on arm circumferences <31.3cm (too small to accomodate the bladder under only strap).[4]

Applications

Application side was block randomized in sets of 10 per tourniquet (SICH, DNIPRO, PULS, Y&B, X8T). Tourniquets were applied over thin scrubs material (Ukrainian-manufactured tourniquets because the edge of the SICH-limb-encricling strap caused a "paper cut" on the first recipient during strap securing through the modified triangle) or skin (X8T) on the mid-arm then same-side mid-thigh of seated recipients with the arm resting palm up on a table and knee flexed approximately 90° with feet on the floor or elevated surface. Distal arterial flow (radial artery, dorsal pedal artery, or posterior tibial artery) was monitored with audible Doppler (Ultrasonic Doppler Flow Detector Model 811 with 9.5MHz adult flat probe; Parks Medical Electronics, Aloha, OR). Arterial occlusion was defined as loss of audible Doppler pulse. Arterial flow return was defined as return of audible Doppler pulse.

After tourniquet placement around the limb with the redirect buckle positioned laterally for downward strap pulling,[12] the applier pulled and secured the strap as tight as possible and removed both hands from the tourniquet for pre-tightening-system-use pressure (Figure 2). Tightening-system use began. For the Ukrainian-manufactured tourniquets, rod rotation was paused at first arterial occlusion (Figure 2), and the rod was secured as soon thereafter as allowed hands-off first completion with no audible pulse (Figure 2).

Rod securing and application completion involved rod placement in the rod-holding part of the tourniquet and completion of additional application securing maneuvers: SICH–rod end in top of modified triangle and any available portion of limb-encircling strap threaded through a slot in the modified triangle;[6] DNIPRO and PULS–rod end in one side of open-top bracket with any available portion of limb-encircling strap placed over rod in bracket and time strap secured across bracket opening;[7,8] Y&B–rod end in triangle.[9]

Returns of arterial flow before 100 seconds from first completion resulted in an additional 180° rod rotation and an additional completion. Pressure thresholds for early application release were set at rod-secured pressures of 800mmHg for arms and 1500mmHg for thighs. Pre-release pressure was taken 100 seconds from first completion or sooner if early release; then the rod was unsecured and slowly unrotated to capture return-of-arterial-flow pressure prior to tourniquet removal.

X8T application differences were as follows: a hands-off first arterial occlusion pressure, first completion pressure one-click-and-hands-off past first occlusion, returns of arterial flow before 100 seconds from first completion resulted in one additional tightening click, and no collection of return-of-arterial-flow pressure during removal process.

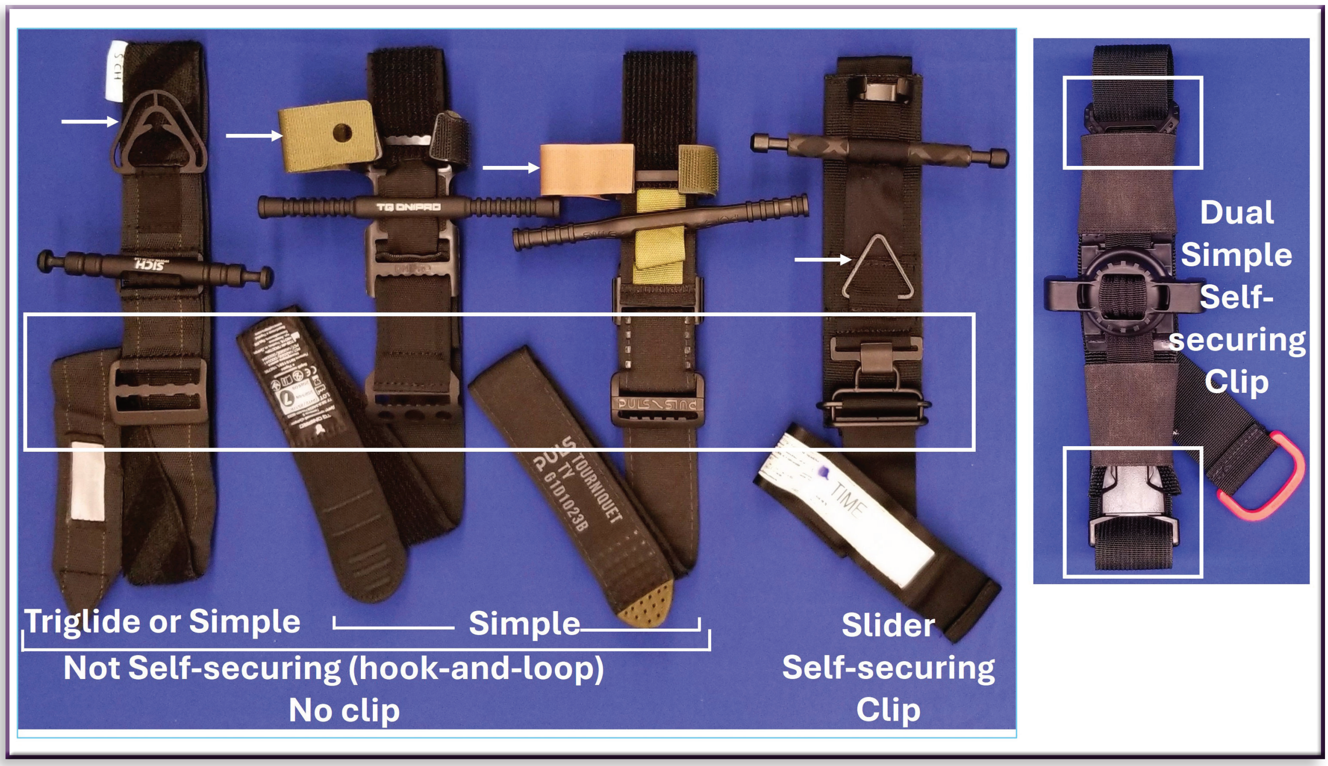
FIGURE 1 *Tourniquets.*

Each tourniquet has a 3.8cm-wide, nonelastic strap that encircles the limb and a base area containing a tightening system and a redirect buckle. Redirect buckles are contained within white outlined rectangles and have a short text description. The securing mechanisms for the windlass rods of the four Ukrainian-manufactured tourniquets are indicated by a white arrow. Left to right: SICH, DNIPRO, PULS, Y&B, X8T.

The SICH, DNIPRO, and PULS use hook-and-loop for strap/redirect system security. The Y&B uses a self-securing slider redirect buckle for strap/redirect security. The metal SICH redirect buckle can be threaded as a simple redirect buckle, which we did using the outer slot, or as a triglide redirect buckle. The DNIPRO and PULS have simple redirect buckles. Only the Y&B has a clip portion of the redirect buckle; the straps of the others must be unthreaded and rethreaded if placing around a trapped limb.

All four have non-self-securing, windlass-rod tightening systems with the SICH, DNIPRO, and Y&B having metal windlass rods. The windlass-rod securing brackets are a modified triangle for the SICH, an open-top bracket for the DNIPRO and PULS, and a triangle for the Y&B. In response to windlass-rod rotations, the SICH, DNIPRO, and PULS have internal-width circumferential strap shortening dependent on direct movement of only the separate, internal strap that passes through a slot in the windlass rod and is contained within and anchored to the wider strap that encircles the limb. Y&B windlass-rod rotations cause full-width circumferential strap shortening via a loop of strap sewn around the windlass rod and attached to the limb-encircling strap via rivets and sewing through a fabric-enclosed, thin, small plate and the clip via sewing. Windlass-rod rotations immediately affect strap pressure with the SICH and Y&B. Slack in the internal strap of the DNIPRO and PULS results in a lack of pressure increase during the first 90° of rod rotation.

The X8T has a self-securing double redirect strap/redirect system that cannot be unthreaded and has a clip for securing around a trapped limb and a self-securing tightening system with unidirectional dial rotation parallel to the limb surface. Dial rotation results in immediate, full-width circumferential strap shortening via shortening of a strap that is sewn around the secondary strap redirect and the clip of the primary strap redirect. Ten teeth advances (10 clicks) create 180° of dial rotation (equivalent to one 180° windlass-rod turn).



Starting with 0° as the beginning position of the windlass rod (perpendicular to the limb-encircling strap), every 180° of tightening-system rotation was considered one turn (10 clicks of the X8T/turn). This differs from counting choices considering 0 turns as the first rod position parallel to the limb-encircling strap (90° rod rotation).[13–15]

PW supervised applications and called Doppler signal loss and return. A separate person collected pressure data and also listened for Doppler signal loss and return. Ukrainian-manufactured tourniquet applications were videoed, and video review was used to help confirm times, pressures, and rod rotations. Recipients could stop applications at any time.

Visual Assessments

Tourniquets were inspected and photographed after each pair of arm and thigh applications. Because of the bending of the thin, small plate involved in the Y&B strap connection, video was shot of Y&Bs after thigh applications.

Resetting and Cleaning

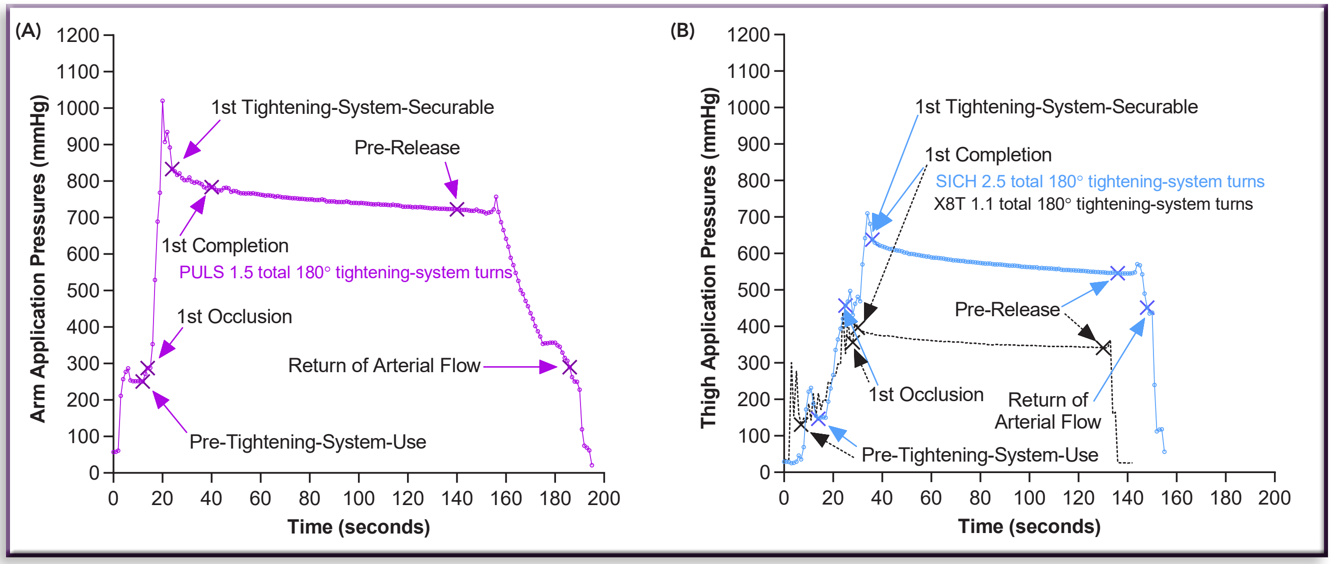
Between arm and thigh applications and after pictures, each tourniquet was reset with untwisting of all strap parts, flattening of Y&B riveted plate piece, and full-length stretching. Each tourniquet was sprayed with 70% denatured ethyl alcohol and allowed to dry between recipients.

Statistical Analysis

Data were organized in Excel for Microsoft 365 MSO (Version 2508 Build 16.0.19127.20082 64-bit; Microsoft Corp., Redmond, WA). Graphing and statistical analyses were performed with GraphPad Prism, version 7.04 for Windows (GraphPad Software Inc., Boston, MA). One-way analysis of variance (ANOVA) and repeated measures one-way ANOVA, both with Tukey's multiple comparisons, were used to compare pressure, tightening-system use, pressure/turn, and speed of additional tightenings between tourniquets. *T*-tests or paired *t*-tests were used for pressure, tightening-system use, pressure/turn comparisons between limbs with a tourniquet, and for first-completion

FIGURE 2 *Example pressure traces.*

Example traces of tourniquet pressures from tourniquet application through tourniquet release and removal. Pressures were collected every second and shown as small open circles with connecting lines. Named pressure and time events are marked by ×'s pointed at by arrows from text indicating the names of the events. Windlass-rod tourniquets often have time between reaching a securable rod position and completing all tourniquet rod- and strap-securing steps. **(A)** Example arm PULS application (magenta) with no return of pulse before release. **(B)** Example thigh SICH (blue) and X8T (black) applications with no return of pulse before release.



versus after-first-completion pressure/turn comparisons. Pearson's correlation was used for circumference versus occlusion pressure and circumference and pre-tightening-system use versus tightening-system use. Chi-square test was used for contingency tables.

Results

Appliers

There were eight appliers (one male, seven females). One female applier only did one recipient's DNIPRO and PULS applications. One female applier did not do any SICH applications. The rest of the appliers had at least one application of each tourniquet.

Recipients

Table 1 has recipient information. Twenty recipients did not receive all four Ukrainian-manufactured tourniquets: seven only had SICH, four only had DNIPRO and PULS, five only had Y&B, and the rest had applications of three of the four Ukrainian-manufactured tourniquets.

Tourniquet-Secured Arterial Occlusion (Successful Completion)

Table 2 has information about achieving hands-off, tourniquet-secured arterial occlusion. As expected,[16] pressures decreased after each completion (completion defined as hands off after securing the tightening system and completing any additional tourniquet-securing steps, Figure 2). One Y&B thigh application never reached completion for physical inability to achieve the needed sixth windlass-rod rotation and secure the rod. One SICH arm application was never completed because the application would have been completed above the 800mmHg arm pressure threshold (was released from the completion position without hands off the tourniquet). Among the 238 other Ukrainian-manufactured tourniquet applications, 26 arm and 43 thigh applications had early pulse return requiring additional tightening (Table 3). Among the 80 X8T applications, all reached completion, and five arm and 28 thigh applications had early pulse return requiring additional tightening (Table 3).

Pressures and Tightening-System Use

Application pressures and tightening-system turns for each Ukrainian-manufactured tourniquet are shown in Figure 3 with dashed black lines indicating interquartile ranges (IQRs) for X8T applications. X8T arm application pressures are only for circumferences >31.2cm; therefore, X8T arm occlusion pressure IQRs higher than those of the Ukrainian-manufactured tourniquets was expected. Thigh occlusion pressures with the full-width tightening X8T were lower than those of each Ukrainian-manufactured tourniquet, including the full-width tightening Y&B. As anticipated because of the X8T's finer resolution tightening system increments, the ranges for the Ukrainian-manufactured tourniquet arm and thigh completion pressures were wider, and most were higher than the X8T's. No thigh applications crossed the greater-than-1500mmHg-at-completion-pressure threshold for early release. No X8T arm applications crossed the greater-than-800mmHg-at-completion-pressure threshold for early release. At first completion, five Ukrainian-manufactured tourniquets crossed the early-release arm pressure threshold (1 SICH-rod into completion position but hands never left the tourniquet, so not hands-off completion before release; 1 DNIPRO; and 3 PULS). Of arm applications requiring additional tightening (5 SICH, 5 DNIPRO, 8 PULS, 8 Y&B, and 3 X8T), eight crossed the early-release pressure threshold (1 SICH, 1 DNIPRO, and 6 PULS).

Occlusion pressures of applications that required additional tightening after the first completion were intermixed with occlusion pressures of applications that did not require additional tightening (Figure 3A, 3B). First completion pressures of applications that required additional tightening were more frequently (but not entirely) in the lower half of all first completion pressures. Pre-release pressures of applications that received additional tightening were predominantly in the upper half of all pre-release pressures.

TABLE 1 *Tourniquet Recipient Information*

	Group; median (minimum, 25th percentile, 75th percentile, maximum)							
	Any tourniquet; n=44	**All 4 Ukrainian tourniquets and X8T; n=22**	**SICH; n=30**	**DNIPRO; n=30**	**PULS; n=30**	**Y&B; n=30**	**X8T; n=40**	**X8T only; n=2**
Sex; F; M	31 F; 13 M	15 F; 7 M	21 F; 9 M	21 F; 9 M	21 F; 9 M	20 F; 10 M	27 F; 13 M	1 F; 1 M
Age, yr	20 (19, 20, 22, 68)	20 (19, 20, 22, 68)	20 (19, 20, 22, 68)	20 (19, 20, 22, 68)	20 (19, 20, 22, 68)	20 (19, 20, 22, 68)	20 (19, 20, 22, 68)	19; 20
Height, cm	169 (152, 163, 180, 193)	168 (152, 159, 180, 193)	168 (152, 163, 180, 193)	168 (152, 160, 180, 193)	168 (152, 160, 180, 193)	169 (152, 162, 181, 193)	170 (152, 163, 180, 193)	163; 191
Weight, kg	69.2 (47.2, 62.3, 94.1, 133.8)	71.4 (47.2, 61.1, 95.3, 133.8)	70.3 (47.2, 62.6, 95.3, 133.8)	69.2 (47.2, 58.4, 95.3, 133.8)	69.2 (47.2, 58.4, 95.3, 133.8)	72.6 (47.2, 63.3, 95.8, 133.8)	71.4 (47.2, 62.8, 95.3, 133.8)	62.1; 81.6
Systolic blood pressure, mmHg	124 (91, 113, 131, 165)	124 (104, 112, 130, 145)	122 (104, 112, 130, 145)	124 (99, 114, 130, 165)	124 (99, 114, 130, 165)	124 (91, 114, 132, 165)	124 (91, 113, 131, 165)	126; 130
Arm circumference, cm	30.5 (23.1, 26.0, 35.2, 40.5)	32.4 (23.1, 27.0, 35.1, 40.5)	31.8 (23.1, 26.6, 35.1, 40.5)	31.8 (23.1, 25.9, 35.1, 40.5)	31.8 (23.1, 25.9, 35.1, 40.5)	32.4 (23.1, 27.0, 35.5, 40.5)	31.3 (23.1, 26.7, 35.4, 40.5)*	27.3; 31.0
Thigh circumference, cm	55.8 (43.7, 51.7, 61.0, 75.5)	57.3 (43.7, 52.2, 61.8, 75.5)	56.0 (43.7, 52.0, 61.3, 75.5)	56.0 (43.7, 51.1, 61.3, 75.5)	56.0 (43.7, 51.1, 61.3, 75.5)	57.8 (43.7, 52.9, 61.8, 75.5)	56.1 (43.7, 52.5, 61.5, 75.5)	53.3; 56.5

Note: Data are for the day and limb on which recipients received the X8T for 40 recipients and the DNIPRO for the 4 recipients who did not receive the X8T.
*n=19 arm X8T pressures group 35.4 (32.0, 32.9, 37.0, 40.5).
F = female; M = male; SICH = Strengthened Individual Combat Hybrid Tourniquet; DNIPRO = TQ DNIPRO GEN 2; PULS = PULS Tourniquet; Y&B = Yellow & Blue tourniquet; X8T = X8T-T2G tourniquet.

TABLE 2 *Tourniquet Occlusion and Application Completion*

	SICH	**DNIPRO**	**PULS**	**Y&B**
Reached occlusion	30 arm, 30 thigh	30 arm, 30 thigh	30 arm, 30 thigh	30 arm, 30 thigh
Secured windlass rod with occlusion (achieved first completion)	29 arm, 30 thigh	30 arm, 30 thigh	30 arm, 30 thigh	30 arm, 29 thigh
Never secured windlass rod for crossing pressure threshold (physically securable, could have achieved first completion)	1 arm (1.5 turns), 0 thigh	0 arm, 0 thigh	0 arm, 0 thigh	0 arm, 0 thigh
Never secured windlass rod because physically unsecurable (could not achieve first completion)	0 arm, 0 thigh	0 arm, 0 thigh	0 arm, 0 thigh	0 arm, 1 thigh (could not secure at 5.5 turns and needed 6.5 turns for occlusion)
Pulse return, restored occlusion but released for time limit before re-securing (physically securable, could have achieved second completion)	0 arm, 0 thigh	0 arm, 0 thigh	0 arm, 0 thigh	0 arm, 0 thigh
Pulse return, restored occlusion but then released for pressure threshold (all physically securable, could have achieved second completion)	1 arm (1.5 turns), 0 thigh	0 arm (1 arm with 1.5 turns should have been released early for threshold but was not), 0 thigh	7 arm (2 arm each with 1.5 turns should have been released early for threshold but were not), 0 thigh	0 arm, 0 thigh
Pulse return and did not manage to re-secure rod before release time limit because physically difficult, unknown if rod physically securable (unknown if could have achieved second completion)	0 arm, 0 thigh	0 arm, 0 thigh	0 arm, 0 thigh	0 arm, 1 thigh (4.5 turns)
Pulse return and physically could not re-secure rod with additional turn (could not achieve second completion)	0 arm, 0 thigh	0 arm, 0 thigh	0 arm, 0 thigh	0 arm, 1 thigh (5.5 turns)
Lost hold of rod trying to secure (did not achieve second completion)	0 arm, 0 thigh	0 arm, 0 thigh	0 arm, 0 thigh	0 arm, 1 thigh (5.5 turns)

Note: Turns refers to 180° tightening-system rotations starting from the beginning position of the windlass rod (perpendicular to the limb-encircling strap).

SICH = Strengthened Individual Combat Hybrid Tourniquet; DNIPRO = TQ DNIPRO GEN 2; PULS = PULS Tourniquet; Y&B = Yellow & Blue tourniquet; X8T = X8T-T2G tourniquet.

TABLE 3 *Tourniquet Need for Tightening-System Use*

	Group; no. of recipients					
	SICH	DNIPRO	PULS	Y&B	X8T	χ^2 *p*-value
Arm, all applications of all tourniquets on all recipients						
1st occlusion occurred without tightening-system use	6	9	10	0	6	.009
1st occlusion required tightening-system use	24	21	20	30	34	
1st occlusion occurred without tightening-system use and no tightening-system use required beyond securing tightening system	1	5	2	NA	4	.159
1st occlusion occurred without tightening-system use but required additional tightening-system use after 1st completion	4	4	8	NA	2	
Additional tightening-system use after 1st completion	5	5	8	8	5	.484
No additional tightening-system use after 1st completion	24	25	22	22	35	
Arm, applications of tourniquets on 22 recipients who received each tourniquet						
1st occlusion required tightening-system use	2	6	7	0	3	.026 (.015)*
1st occlusion occurred without tightening-system use and no tightening-system use required beyond securing tightening system	20	16	15	22	19	
1st occlusion occurred without tightening-system use but required additional tightening-system use after 1st completion	1	4	1	NA	1	NA
Additional tightening-system use after 1st completion	1	2	6	NA	2	
No additional tightening-system use after 1st completion	5	3	6	6	3	.632 (.671)*
1st occlusion required tightening-system use	16	19	16	16	19	
Thigh, all applications of all tourniquets on all recipients						
1st occlusion occurred without tightening-system use	0	0	0	0	0	NA
Additional tightening-system use after 1st completion	11	9	8	15	28	.001
No additional tightening-system use after 1st completion	19	21	22	14	12	
Thigh, applications of tourniquets on 22 recipients who received each tourniquet						
Additional tightening-system use after 1st completion	8	7	7	11	17	.010 (.460)*
No additional tightening-system use after 1st completion	14	15	15	10	5	

**P* values before the parentheses are for χ^2 comparisons for all five tourniquets; *p* values in parentheses are for chi-square comparisons for only the four Ukrainian-manufactured tourniquets.
SICH = Strengthened Individual Combat Hybrid Tourniquet; DNIPRO = TQ DNIPRO GEN 2; PULS = PULS Tourniquet; Y&B = Yellow & Blue tourniquet; X8T = X8T-T2G tourniquet; NA = not applicable.

No X8T pressures were over 500mmHg. No arm occlusion pressures were over 500mmHg (Figure 3A). Among the Ukrainian-manufactured tourniquets, pressures over 500mmHg occurred in 39 arm first completions (9 SICH, 13 DNIPRO, 16 PULS, 1 Y&B), 49 arm pre-releases (12 SICH, 11 DNIPRO, 24 PULS, 2 Y&B), 10 thigh occlusions (3 SICH, 4 DNIPRO, 2 PULS, 1 Y&B), 67 thigh first completions (19 SICH, 19 DNIPRO, 18 PULS, 11 Y&B), and 83 thigh pre-releases (21 SICH, 22 DNIPRO, 23 PULS, 17 Y&B) (Figure 3A, 3B).

Within each application across all five designs, 99 of 101 per-turn, after-first-completion pressure increases were greater than per-turn, first-completion pressure increases (Figure 3D). Arm applications generally had higher per-turn, first-completion pressure increases and higher per-turn, after-first-completion pressure increases than leg applications (Figure 3D). Compared to the other tourniquets, Y&B per-turn pressure increases were lower, and PULS per-turn pressure increases tended to be higher.

As expected,[17–19] larger circumference limbs required higher pressures for occlusion ($p<.0001$ each tourniquet). Larger circumference limbs and lower achieved pre-tightening-system-use pressures (Figure 3A, 3B) were both associated with needing more total turns of the tightening system (circumference $p<.0001$, pre-tightening system use $p=.096$ for Y&B and $p<.0002$ for others, Figure 3C). Difficulty securing the Y&B rod in the triangle was caused by turn-related rod migration (Table 2).

The median (IQR) times from audible pulse detection to hands-off after completion of an additional windlass-rod turn were as follows: SICH 10 (9, 15) seconds ($p=.028$ versus DNIPRO, $p=.005$ versus PULS), DNIPRO 18 (13, 21) seconds, PULS 17 (16, 20) seconds, Y&B 12 (11, 18) seconds ($p=.058$ versus PULS, but does not include non-secured Y&Bs).

Tourniquet Signs of Wear

With 30 arm and 30 thigh uses for each Ukrainian-manufactured tourniquet, none became unusable. Each required resetting between uses, including thorough untwisting of the inner straps of the SICH, DNIPRO, and PULS. Y&B resetting included flattening of the fabric-enclosed, thin, small plate after most thigh applications. The base plates of the DNIPRO and PULS did not require any repositioning as part of tourniquet resetting.

FIGURE 3 *Tourniquet pressures and tightening-system use.*

For each Ukrainian-manufactured tourniquet, each application is shown with a circle; the whiskers extend from minimum to maximum; the boxes extend from the 25th percentile to 75th percentile (bounding the IQR for each Ukrainian-manufactured tourniquet); and the medians are inside the boxes and sometimes obscured by the circles. Data for SICH applications are blue, for DNIPRO are green, for PULS are purple, and for Y&B are brown. Data for Ukrainian-manufactured tourniquet applications that required additional tightening after the first completion have circles with red-filled centers.

IQRs for X8T applications are indicated by dashed lines at the 25th percentile and 75th percentile (n=19 for X8T arm pressures; n=40 for X8T thigh pressures and arm and thigh tightening-system use; n=17 for X8T arm per-turn, first-completion pressure increases; n=4 for X8T arm per-turn, additional-tightening pressure increases; n=40 for X8T thigh per-turn, 1st-completion pressure increases; n=32 for X8T thigh per-turn, additional-tightening pressure increases). All *p* values ≤.2 are reported.

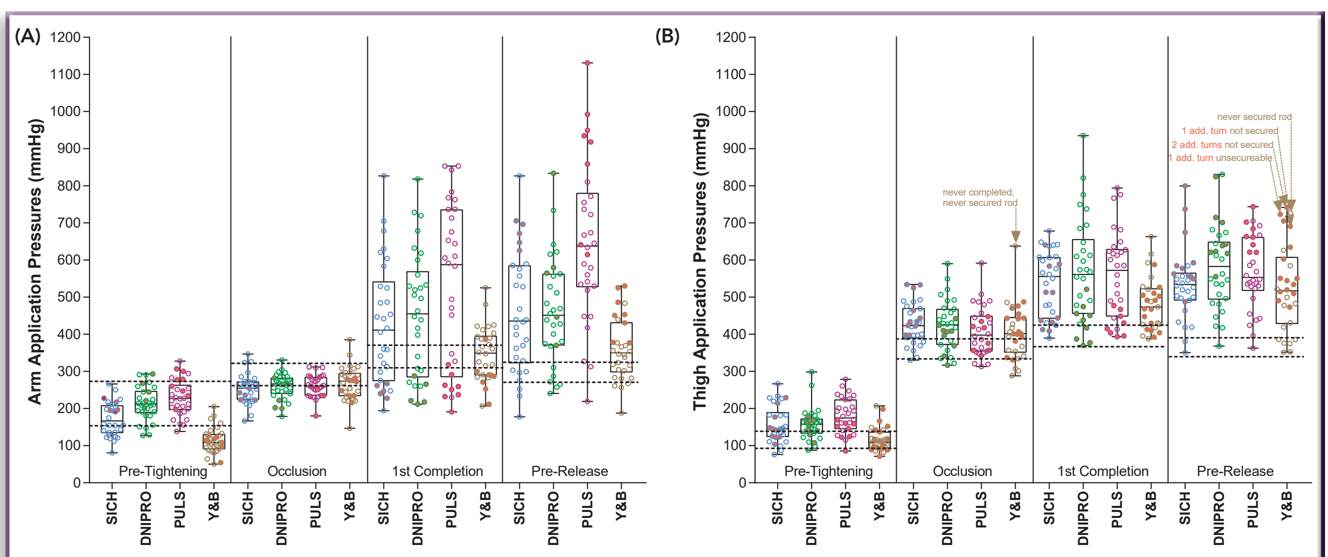
For almost every tourniquet, arm pre-tightening-system-use pressures were higher than thigh (SICH *p*=.044, DNIPRO *p*<.0001, PULS *p*<.0001, Y&B *p*=.757, X8T *p*<.0001); thigh occlusion pressures were higher than arm (*p*<.0001 for each tourniquet), and thigh applications involved more tightening-system 180° turns (*p*<.0001 for each tourniquet). Median arm 1st completion pressures and pre-release pressures were higher than thigh with the PULS (1st completion *p*=.490, pre-release *p*=.060). In contrast, median arm 1st completion and pre-release pressures were lower than thigh pressures with every other tourniquet (1st completion *p*<.006 SICH, DNIPRO, Y&B, and X8T; pre-release *p*<.040 SICH and *p*<.0007 DNIPRO, Y&B, and X8T).

(A) Arm Application Pressures. *P* values ≤.2 for pressure comparisons between the tourniquets are as follows:

- Pre-Tightening-System-Use Pressures: mmHg medians SICH 166, DNIPRO 212, PULS 227, Y&B 108, X8T 197; one-way ANOVA: *p*≤.010 SICH<DNIPRO; *p*=.0001 SICH<PULS; *p*<.0001 Y&B<SICH, DNIPRO, PULS, and X8T; *p*=.165 SICH<X8T. Repeated measures one-way ANOVA only Ukrainian-manufactured tourniquets: *p*=.017 SICH<DNIPRO; *p*=.0005 SICH<PULS; *p*≤.004 Y&B<SICH, DNIPRO, and PULS.
- Occlusion Pressures: mmHg medians SICH 255, DNIPRO 266, PULS 260, Y&B 274, X8T 298; one-way ANOVA: *p*=.038 SICH<X8T and *p*=.166 DNIPRO<X8T. Repeated measures one-way ANOVA only Ukrainian-manufactured tourniquets: no *p* values<.572.
- 1st Completion Pressures: mmHg medians SICH 411, DNIPRO 455, PULS 588, Y&B 349, X8T 338; one-way ANOVA: *p*=.107 SICH<PULS, *p*=.069 DNIPRO>Y&B, *p*=.070 DNIPRO>X8T, *p*≤.0004 PULS>Y&B and X8T. Repeated measures one-way ANOVA only Ukrainian-manufactured tourniquets: *p*=.124 SICH>Y&B, *p*=.032 DNIPRO>Y&B, *p*=.002 PULS>Y&B.
- Pre-Release Pressures: mmHg medians SICH 436, DNIPRO 451, PULS 638, Y&B 350, X8T 304; one-way ANOVA: *p*=.078 SICH>Y&B, *p*<.002 SICH<PULS and >X8T, *p*<.002 DNIPRO<PULS and >X8T, *p*<.0001 PULS>Y&B and X8T, *p*=.058 DNIPRO>Y&B. Repeated measures one-way ANOVA only Ukrainian manufactured tourniquets: *p*=.0182 SICH<PULS, *p*=.0137 SICH>Y&B, *p*=.0002 DNIPRO<PULS, *p*=.0185 DNIPRO>Y&B, *p*<.0001 PULS>Y&B.

(B) Thigh Application Pressures. *P* values ≤.2 for pressure comparisons between tourniquets are as follows:

- Pre-Tightening-System-Use Pressures: mmHg medians SICH 145, DNIPRO 158, PULS 175, Y&B 109, X8T 122; one-way ANOVA: *p*=.196 SICH<PULS; *p*<.003 Y&B<SICH, DNIPRO, and PULS; *p*<.005 X8T<SICH, DNIPRO, and PULS. Repeated measures one-way ANOVA: *p*=.012 SICH>Y&B; *p*=.052 SICH>X8T; *p*=.190 DNIPRO<PULS; *p*=.0002 Y&B<DNIPRO and PULS; *p*≤.01 X8T<DNIPRO and PULS. Repeated measures one-way ANOVA only Ukrainian-manufactured tourniquets: *p*=.180 SICH<PULS; *p*=.135 DNIPRO<PULS; *p*<.008 Y&B<SICH, DNIPRO, and PULS.
- Occlusion Pressures: mmHg medians SICH 423, DNIPRO 426, PULS 398, Y&B 402, X8T 359; one-way ANOVA: *p*≤.0003 X8T<SICH and DNIPRO, *p*=.019 X8T<PULS, *p*=.030 X8T<Y&B. Repeated measures one-way ANOVA: *p*=.128 SICH>Y&B; *p*<.002 X8T<SICH, DNIPRO, and PULS; *p*=.108 X8T<Y&B. Repeated measures one-way ANOVA only Ukrainian-manufactured tourniquets: *p*=.089 SICH>Y&B.
- 1st Completion Pressures: mmHg medians SICH 556, DNIPRO 562, PULS 572, Y&B 474, X8T 393; one-way ANOVA: *p*=.190 SICH>Y&B; *p*<.003 X8T<SICH, DNIPRO, PULS, and Y&B; *p*=.005 DNIPRO>Y&B; *p*=.022 PULS>Y&B. Repeated measures one-way ANOVA: *p*=.197 SICH>Y&B; *p*≤.0008 X8T<SICH, DNIPRO, PULS, and Y&B; p=.029 DNIPRO>Y&B; p=.024 PULS>Y&B. Repeated measures one-way ANOVA only Ukrainian-manufactured tourniquets: *p*=.140 SICH>Y&B, *p*=.019 DNIPRO>Y&B, *p*=.016 PULS>Y&B.
- Pre-Release Pressures: mmHg medians SICH 534, DNIPRO 583, PULS 553, Y&B 517, X8T 367; one-way ANOVA: *p*<.0001 X8T<SICH, DNIPRO, PULS, and Y&B; *p*=.149 DNIPRO>Y&B. Repeated measures one-way ANOVA: *p*<.0001 X8T<SICH, DNIPRO, PULS, and Y&B; *p*=.073 DNIPRO>Y&B; *p*=.095 PULS>Y&B. Repeated measures one-way ANOVA only Ukrainian-manufactured tourniquets: *p*=.049 DNIPRO>Y&B, *p*=.065 PULS>Y&B.



(continues)

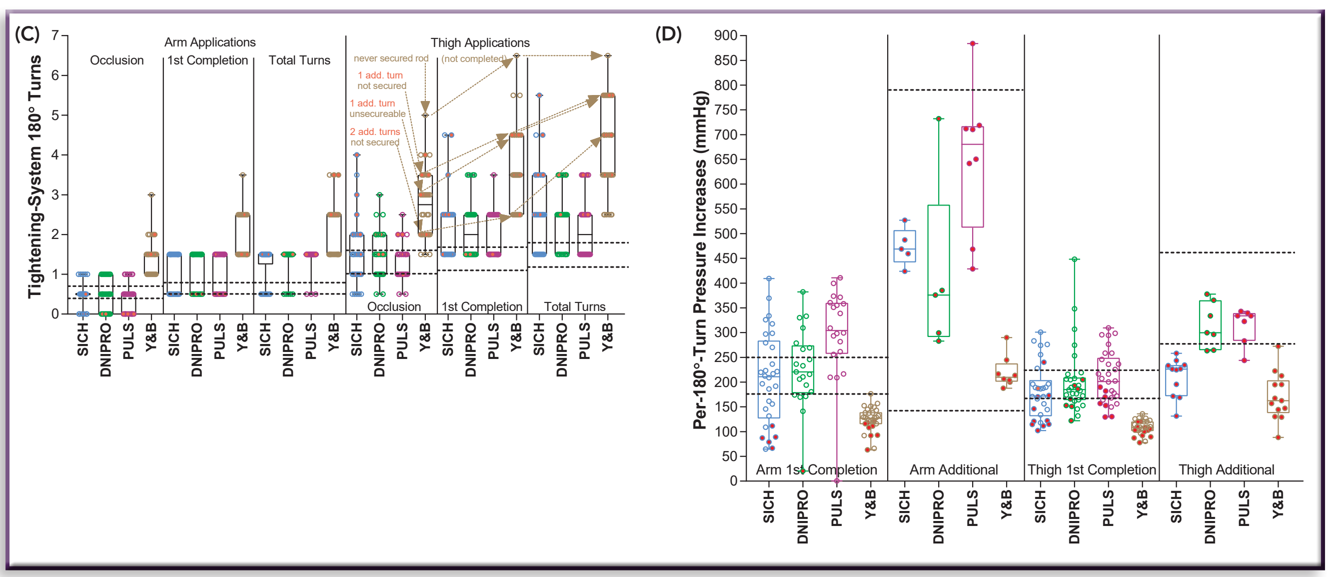
FIGURE 3 *Cont.*

(C) Occlusion, 1st Completion, and Total Tightening-System 180° Turns. P values ≤.2 for turns comparisons between tourniquets are as follows:

- Arm Occlusion Tightening-System Turns (to the closest 0.5 turn): medians SICH 0.5, DNIPRO 0.5, PULS 0.5, Y&B 1.5, X8T 0.5; one-way ANOVA: $p<.0001$ Y&B>SICH, DNIPRO, PULS, and X8T. Repeated measures one-way ANOVA: $p<.0001$ Y&B>SICH, DNIPRO, PULS, and X8T. Repeated measures one-way ANOVA only Ukrainian-manufactured tourniquets: $p<.0001$ Y&B>SICH, DNIPRO, and PULS.
- Arm 1st Completion Tightening-System Turns: medians SICH 1.5, DNIPRO 1.5, PULS 1.5, Y&B 1.5, X8T 0.6; one-way ANOVA: $p<.0001$ X8T<SICH, DNIPRO, PULS, and Y&B; $p<.0001$ Y&B>SICH, DNIPRO, and PULS. Repeated measures one-way ANOVA: $p<.003$ X8T<SICH, DNIPRO, PULS, and Y&B; $p<.004$ Y&B>SICH, DNIPRO, and PULS. Repeated measures one-way ANOVA only Ukrainian-manufactured tourniquets: $p<.002$ Y&B>SICH, DNIPRO, and PULS.
- Arm Total Tightening-System Turns: medians SICH 1.5, DNIPRO 1.5, PULS 1.5, Y&B 2.5, X8T 0.7; one-way ANOVA: $p<.0001$ X8T<SICH, DNIPRO, PULS, and Y&B; $p<.0001$ Y&B>SICH, DNIPRO, and PULS. Repeated measures one-way ANOVA: $p<.0001$ X8T<SICH, DNIPRO, PULS, and Y&B; $p<.003$ Y&B>SICH, DNIPRO, and PULS. Repeated measures one-way ANOVA only Ukrainian-manufactured tourniquets: $p<.002$ Y&B>SICH, DNIPRO, and PULS.
- Thigh Occlusion Tightening-System Turns: medians SICH 1.5, DNIPRO 1.5, PULS 1.0, Y&B 2.8, X8T 1.3; one-way ANOVA: $p<.0001$ Y&B>SICH, DNIPRO, PULS, and X8T. Repeated measures one-way ANOVA: $p<.0001$ Y&B>SICH, DNIPRO, PULS, and X8T. Repeated measures one-way ANOVA only Ukrainian-manufactured tourniquets: $p<.0001$ Y&B>SICH, DNIPRO, and PULS.
- Thigh 1st Completion Tightening-System Turns: medians SICH 2.5, DNIPRO 2.0, PULS 1.5, Y&B 3.5, X8T 1.4; one-way ANOVA: $p<.005$ X8T<SICH, DNIPRO, and Y&B; $p<.0001$ Y&B>SICH, DNIPRO, and PULS; $p=.188$ SICH>PULS. Repeated measures one-way ANOVA: $p<.02$ X8T<SICH, DNIPRO, and Y&B; $p<.0006$ Y&B>SICH, DNIPRO, PULS, and X8T. Repeated measures one-way ANOVA only Ukrainian-manufactured tourniquets: $p\leq.0003$ Y&B>SICH, DNIPRO, and PULS; $p=.152$ SICH>PULS; $p=.069$ DNIPRO>PULS.
- Thigh Total Tightening-System Turns: medians SICH 2.5, DNIPRO 2.5, PULS 2.0, Y&B 3.5, X8T 1.5; one-way ANOVA: $p\leq.0004$ X8T<SICH, DNIPRO, and Y&B; $p=.072$ X8T<PULS; $p<.0001$ Y&B>SICH, DNIPRO, and PULS. Repeated measures one-way ANOVA: $p\leq.0003$ X8T<SICH, DNIPRO, and Y&B; $p=.102$ X8T<PULS; $p<.0001$ Y&B>SICH, DNIPRO, and PULS. Repeated measures one-way ANOVA only Ukrainian-manufactured tourniquets: $p<.0001$ Y&B>SICH, DNIPRO, and PULS; $p=.069$ DNIPRO>PULS.

(D) Per-180°-Turn Pressure Increases. First completion pressure changes were excluded for the nine DNIPRO and 10 PULS applications with occlusion before tightening-system use because these tourniquets do not begin tightening in response to windlass-rod turning until approximately 90° of rod rotation has occurred. Arm per-turn pressure increases were higher than thigh (all five tourniquets combined paired t-test $p<.0001$). In 99 of 101 applications with tightening after first completion, additional per-turn pressure increases were greater than per-turn, first-completion pressure increases. P values ≤.2 for per-turn pressure increase comparisons between the tourniquets are as follows:

- Arm 1st Completion: mmHg medians SICH 211, DNIPRO 221, PULS 309, Y&B 127, X8T 192; one-way ANOVA: $p<.0004$ Y&B<SICH, DNIPRO, PULS, and X8T; $p<.002$ PULS>SICH, DNIPRO, and X8T.
- Arm Additional: mmHg medians SICH 469, DNIPRO 376, PULS 681, Y&B 210, X8T 454; one-way ANOVA: $p=.077$ Y&B<SICH, $p=.0001$ Y&B<PULS, $p=.138$ Y&B<X8T; $p=.109$ PULS>DNIPRO.
- Thigh 1st Completion: mmHg medians SICH 172, DNIPRO 185, PULS 201, Y&B 109, X8T 196; one-way ANOVA: $p<.0001$ Y&B<SICH, DNIPRO, PULS, and X8T; $p=.195$ PULS>SICH.
- Thigh Additional: mmHg medians SICH 226, DNIPRO 300, PULS 334, Y&B 163, X8T 367; one-way ANOVA: $p<.007$ Y&B<DNIPRO, PULS, and X8T; $p=.103$ SICH<DNIPRO; $p=.104$ SICH<PULS; $p<.0001$ SICH<X8T.



SICHs developed a small amount of fraying of the sides of the sewn-on area on which to write application time. SICHs developed fraying of the base area strap under the opening through which the inner strap passed upward and through the slot in the windlass rod (Figure 4A).

DNIPROs and PULSs did not develop any visible evidence of wear.

The Y&B applied to left arms and thighs developed stitching failures with increasing separation of the plate-adjacent layers of strap fabric held together by the broken and pulling apart threads (Figure 4B) and separation of the loop of strap sewn around the windlass rod (only on the side away from the plate-adjacent stitching failure, Figure 4B). Y&B plate bending in left thigh applications was always downward in the middle of the plate (Figure 4C) and, for each of the three left thigh applications with 5.5 total windlass-rod turns, involved visibly greater plate deformation than occurred in 5.5-turn right thigh applications. Stitching failure of the loop around the rod became visible after the second thigh application (first and second left 3.5-turn thigh applications). The plate-adjacent broken threads did not become visible until the seventh thigh application, which was the third left 5.5-turn application (Figure 4B). With 4.5 total turns, the eleventh left thigh application had a popping sound, a very bent plate (like Figure 4C), more plate-adjacent stitching pulled apart, and the edge and corner of the plate easily visible. The following two 4.5-turn (of three), one 3.5-turn (of seven), and one 2.5-turn (of two) left applications did not appear to worsen the plate-adjacent stitching separation.

The Y&B applied to right arms and thighs developed stitching failure with separation of the loop of strap sewn around the windlass rod (same loop side as left Y&B). The stitching failure was visible after the second thigh application, which was also the second 4.5-turn thigh application. Right thigh Y&B plate bendings were always upward in the middle of the plate and greatest with 6.5 total windlass-rod turns. The four 5.5-turn right thigh applications had visibly less bending than the 6.5-turn right thigh application. Bending with <5.5 turns was mild (three thigh applications with 4.5 total turns, three with 3.5, and four with 2.5).

Y&B clips became slightly more open during uses. This made unclipping and reclipping even easier and did not appear

FIGURE 4 *Visible tourniquet wear.*

(A) LEFT TO RIGHT: SICH base-area strap under the windlass rod of the orange tourniquet after applied to 30 left arms and 30 left thighs, the never-applied black tourniquet, and the green tourniquet after applied to 30 right arms and 30 right thighs. **(B)** Y&B areas of thread failures and ongoing strap-fabric separation after applied to 30 left arms and 30 left thighs. The sharp corner and edges of the thin plastic plate between the two layers of fabric are visible in the separation, and the remaining threads between the two separating layers are visible above the top edge of the plate. (Shiny plate edge is located toward the bottom and right of center of the picture; remaining threads are located above the top of the plate and below the red stitching.) Strap-fabric separation only occurred on the shown side. The rivets are not shown and had no visible evidence of impending failure. On the opposite side from the failed thread and separating fabric over the plate, the threads involved in holding the strap around the windlass rod were failing (located top center of the picture). **(C)** Downward Y&B plate bending from the first 5.5 total windlass-rod turns application (4th left thigh application).

likely to progress to a clip sufficiently open to not function. However, the unintentional increasing of clip opening suggests compressive force might easily close the clip opening to a non-functioning degree.

Quality Control/Design Consistency

With only four of each Ukrainian-manufactured tourniquet, we did not see any DNIPRO or PULS tourniquet-to-tourniquet differences. There were SICH differences in opening width between the two inward prongs of the modified triangle, which slightly impacted ease of rod securing. There were SICH differences in the length of fabric securing the modified triangle to the base area, which had no functional impact. There were Y&B differences in length, edge-to-edge location, and number of stitching passes creating the strap loop around the windlass rod.

General Design Considerations

All the tourniquets were long enough to apply on the 75.5cm-circumference, largest recipient thigh (lengths: SICH 96.6cm, DNIPRO 93.5cm, PULS 94.0cm, Y&B 109.2cm). The SICH, DNIPRO, and PULS were not long enough to use the base-area strap-securing features in 13, 14, and 8 recipients, respectively. As noted in Table 2, only the Y&B had applications that physically could not be secured. Table 4 lists design thoughts for Ukrainian-manufactured tourniquets.

Discussion

The key finding was the SICH, DNIPRO, and PULS always achieved completable occlusion, but the Y&B did not. Additionally, the Y&B had a slider redirect buckle that, when unthreaded, readily separated into two pieces for easy loss of the slider and also offered multiple incorrect rethreading options; a windlass rod that could be removed from the strap; and inadequate mobility of the rod-securing triangle preventing always being able to secure the windlass-rod.

Achievement and maintenance of arterial occlusion until intentional release (for time or pressure) occurred with every SICH, DNIPRO, and PULS application and every arm Y&B application. Y&B problems occurred during thigh applications. Turn-related rod migration too close to the triangle caused two instances of confirmed physical preclusion of rod securing. Turn-related rod migration also caused two instances of applier struggling with and not securing the rod that were not confirmed to be from physical preclusion before hold on the rod was lost or application was released for time. The Y&B slider-redirect-associated-strap-pulling friction promoted lower pre-tightening-system pressures (Figure 3A, 3B), which translates to more windlass-rod turns with accompanying rod migration (≥3 rod turns in three of 30 arm and 24 of 30 thigh applications, Figure 3C). Rod-turn data from United States-military-combat-related applications of Combat Application Tourniquets® (CAT, CAT Resources, Rock Hill, SC) shows 79% of applications involved ≥3 rod turns, despite 37% of applications using the relatively low-friction simple-redirect-buckle strap routing.[15] Therefore, we expect the Y&B failure incidence on thighs would increase in non-ideal settings.

Research with different recipients shows the 3.8cm-wide CAT requires higher pressures to reach thigh arterial occlusion (median 424, IQR 375-485mmHg) than does the 3.8cm-wide Tactical Ratcheting Medical Tourniquet (Tac RMT; m2inc., Colchester, VT. 338, 356-415mmHg) or the 3.8cm-wide Special Operations Forces Tactical Tourniquet Generation 3 (SOFTTW3; TacMed Solutions™, Anderson, SC. 348, 317-384mmHg).[20] We believe this results from the CAT's not-full-limb-encircling-strap-width-tightening design (only the 2.54cm-wide inner band actually tightens). Having similar tightening designs, we expected and found the SICH, DNIPRO, and PULS to have higher thigh occlusion pressures than the X8T on the same recipients (medians of 423, 426, and 398mmHg versus 359mmHg, Figure 3B). Surprisingly, the Y&B occlusion pressures (median 402mmHg) were also higher than the X8T's; perhaps this relates to the attachment of the Y&B's limb-encircling strap being less than full width and possibly creating centralized pressure.

The occlusion-pressure differences between windlass-rod-tightened tourniquets and tourniquets with finer-resolution tightening systems may be clinically unexciting. However, this study shows once again[13,20] that tourniquets using tightening systems involving 180° windlass-rod rotations frequently have completion pressures hundreds of mmHg higher than necessary and much higher than 500mmHg, even when applications are restricted to only as tight as necessary for completion with occlusion. Considering the respective occlusion pressures and tissue volumes protecting major nerves, the number of arm applications with completion pressures greater than 500mmHg is even more concerning for windlass-rod tourniquets than is the number of thigh applications. Non-arterially occlusive tourniquets are life- and limb-threatening,[1,21] but tourniquet-pressure-related nerve injuries are also undesirable and relate to both the duration and magnitude of pressure. The classic study to reference for 500mmHg and higher being undesirable involved a maximum duration of only three hours.[22] Combat-related tourniquet times in the Russo-Ukrainian War often exceed three hours,[23–25] and in the United States military, sometimes exceed three hours.[1,26]

Resolution of tightening-system-pressure increases becomes increasingly important as tourniquet pressure increases. The magnitude of pressure increase per 180° turn is not linear. Instead, the increase per turn is greater when the turn starts from a higher pressure (note the Figure 3D greater increases per turn for turns occurring after first completion and the association of lower Y&B pre-tightening pressures in Figures 3A and B with lower Y&B first-completion pressure increases per turn in Figure 3D). A possible trade-off for the poor tightening resolution of windlass-rod tightening systems is the potential to slowly decrease tourniquet pressure during removal for conversion or definitive care. Flow data from collapsed-tubes studies suggests the extent of this possible benefit regarding how quickly how much blood flow hits any developed clots is questionable.[27,28]

Regarding wear, the visible Y&B stitching failures did not occur with one use but would clearly be concerning in situations involving tourniquet reuses. If the other Y&B major design problems were addressed, the stitching should also be strengthened. Any tourniquet reuse situations should involve tourniquet visual examinations, complete resetting including full untwisting of all straps and checking for base-plate migration (happens with CAT[14] but did not with DNIPRO or PULS), and consideration of reuse risk-to-benefit ratios.

As noted in Table 4, all four Ukrainian-manufactured tourniquets had designs that avoided creating recipient pain for no functional gain. This should be the case for all tourniquets.

TABLE 4 *Tourniquet Design Thoughts*

Tourniquet	Liked	Considerations
SICH	Limb-encircling strap: – hook and loop adhered equivalently for all 30 applications	Limb-encircling strap: – sharp edge cut skin when pulled through side slot of the rod-securing modified triangle (consider oversewing or other edge change) – end triangular tab catches on strap-securing part of triangle when releasing (consider zigzag stitch or other end change) – with reuses, wear occurs under the windlass rod – consider making strap longer so it can still be pulled through securing triangle when on medium to large thighs*
	Inner strap: – no unnecessary slack so tightening starts when rod rotation starts	Inner strap: – no considerations
	Base area: – very flexible, can secure strap and use tightening system on 14.0cm-circumference cylinder – no sharp edges pushing into skin – restricted opening through which the inner strap goes up to the rod may help keep the rod a securable distance from the securing triangle	Base area: – with reuses, wear occurs in the restricted opening under the windlass rod
	Redirect buckle (simple or triglide): – can be simple threaded for easier development of strap-pull tension – can be triglide threaded to encourage hook-and-loop interaction for better strap security – metal, seems robust – easy threading (good-sized openings)	Redirect buckle (simple or triglide): – could consider rounding the strap-engaged edge when threaded as a simple redirect (for lower friction when pulling the redirected strap tight around the limb)
	Windlass rod: – metal, seems robust – strap through rod with rounded slot edges – remained a securable distance from securing triangle with up to 5.5 total turns of 180° each	Windlass rod: – no considerations
	Triangle rod- and strap-securing system: – metal, seems robust – good rod-securing system (easy use in lab) – seems like a good strap-securing system (easy use in lab when strap long enough for use)	Triangle rod-securing system: – slight differences among tourniquets in the opening width between the two inward prongs near the top of the triangle
DNIPRO	Limb-encircling strap: – hook-and-loop adhered equivalently for all 30 applications	Limb-encircling strap: – consider making strap longer so it can still be secured under the time strap across the top of the top-opening bracket when on medium to large thighs*
	Inner strap: – see considerations	Inner strap: – unnecessary slack, delays start of tightening until approximately 90° of rod rotation†
	Base area/strap connection: – relationship of base plate and strap remains consistent over multiple uses (30 lab uses)	Base area/strap connection: – no considerations
	Base area: – edges rounded for least skin discomfort – no exposed hook of hook-and-loop pushing into skin	Base area: – 9cm-long plate strongly resists tight radius, not very flexible for smaller circumference limb segments
	Redirect buckle (simple): – simple redirect for easy development of strap-pull tension – simple redirect for limited threading choices – metal, seems robust – easy threading (good-sized opening)	Redirect buckle (simple): – could consider smoothing and rounding the strap-engaged edge (for lower friction when pulling the redirected strap tight around the limb)
	Windlass rod: – metal, seems robust – strap through rod with rounded slot edges – remained a securable distance from securing bracket with up to 3.5 total turns of 180° each	Windlass rod: – no considerations
	Top-opening bracket rod- and strap-securing system: – easy to place rod into (in lab)	Top-opening bracket rod- and strap-securing system: – some interference with rod turning

(continues)

TABLE 4 *Cont.*

Tourniquet	Liked	Considerations
PULS	Limb-encircling strap: – hook-and-loop adhered equivalently for all 30 applications	Limb-encircling strap: – consider making strap longer so it can still be secured under the time strap across the top of the top-opening bracket when on medium to large thighs*
	Inner strap: – see considerations	Inner strap: – unnecessary slack, delays start of tightening until approximately 90° of rod rotation†
	Base area/strap connection: – relationship of base plate and strap remains consistent over multiple uses (30 lab uses)	Base area/strap connection: – no considerations
	Base area: – edges rounded for least skin discomfort – strong attempt at no exposed hooks of hook-and-loop pushing into skin – 9cm-long base plate more flexible than DNIPRO, can tighten secure strap and use tightening system on 14.0cm-circumference cylinder	Base area: – a few exposed hooks of hook-and-loop pushing into skin
	Redirect buckle (simple): – simple redirect for easy development of strap pull tension – simple redirect for limited threading choices – easy threading (good-sized opening)	Redirect buckle (simple): – could consider smoothing and rounding the strap-engaged edge (for lower friction when pulling the redirected strap tight around the limb)
	Windlass rod: – strap through rod with rounded slot edges – remained a securable distance from securing bracket with up to 3.5 total turns of 180° each	Windlass rod: – no considerations
	Top-opening bracket rod- and strap-securing system: – easy to place rod into (in lab)	Top-opening bracket rod- and strap-securing system: – some interference with rod turning
Y&B	Limb-encircling strap: – no unnecessary slack so tightening starts when rod rotation starts	Limb-encircling strap: – sewing of loop around windlass rod can start failing with multiple uses – attachment between limb-encircling strap part and windlass-rod-encircling strap part develops a mangled plate, failing stitches, and exposure of corners of the plate with multiple windlass-rod turns in multiple uses – strap sewn around rod can be slid completely off rod, as can rod "grips" (**Major Problem**)
	Base area: – more flexible than DNIPRO, can secure strap and use tightening system on 16.5cm-circumference cylinder – no sharp edges pushing into skin	Base area: – no considerations
	Redirect buckle (slider): – self-securing	Redirect buckle (slider): – difficult to develop good strap pull tension, results in more windlass rod turns needed than a simple redirect – can be unthreaded and has many rethreading possibilities with correct rethreading not obvious (**Major Problem**) – when unthreaded, becomes two separate pieces for easy loss of parts (**Major Problem**)
	Clip of redirect buckle: – clip option to avoid need for unthreading – clip obvious and easy to use	Clip of redirect buckle: – not very robust as opened more during lab uses (concern that might therefore easily be compressed closed)
	Windlass rod: – metal, seems robust	Windlass rod: – slide-on grips on each side of the rod are easy to slide off, which allows easy movement of the rod completely out of the sewn loop of strap, resulting in no tightening system (**Major Problem**) – did not remain a securable distance from securing triangle with 4.5 or more turns of 180° each (**Major Problem**)
	Top-opening bracket for temporary holding of windlass rod: – see considerations	Top-opening bracket for temporary holding of windlass rod: – not functional in lab use (Radius of limbs precluded use of bracket with use of triangle, and triangle provides better rod security. Recommend removing bracket or replacing with a second triangle option.)
	Triangle rod-securing system: – see considerations	Triangle rod-securing system: – rod migration during turns can preclude rod securing in triangle (**Major Problem**)‡

*We suggest all tourniquets using hook-and-loop as part of limb-encircling strap security should consider a sufficiently long strap that any strap-securing features of the base area should be usable even on limb circumferences>56cm.
†We suggest that having slack in the inner strap such that no limb-encircling strap tightening begins until after 90° of rod rotation have occurred is suboptimal because delays in increasing tourniquet pressure are delays in stopping bleeding.
‡We did not try to slide the grips and then the rod within the sewn strap loop.
SICH = SICH tourniquet; DNIPRO = DNIPRO tourniquet; PULS = PULS tourniquet; Y&B = Yellow & Blue tourniquet.

We suggest all tourniquet designs using hook-and-loop-limb-encircling straps should consider having a sufficiently long limb-encircling strap that any base-area-strap-securing features of the tightening system should be usable in all applications, even applications on average to large circumference thighs. The United States military thigh circumference used for setting length requirements was 71.46cm as the 99th percentile for males in 1988.[29] The 99th percentile increased to 77.40cm in 2012.[30] The Committee on Tactical Combat Casualty Care length statement[31] requires only sufficient length for application on a 71.46cm-circumference thigh or 95.25cm of tourniquet total length, which is insufficient to allow the free end to reach the base area on thighs larger than approximately 56cm circumference (50% of the thighs in this study). With hook-and-loop-limb-encircling straps, tourniquet lengths of 139cm (44cm additional) would be required to engage base-area security on thighs of 71.46cm. Negatives to such strap-length increases would include increased tourniquet weight and volume, and additional strap to unthread and rethread through the redirect buckle.

As an additional general design consideration, we believe tourniquet tightening should begin as soon as the tightening system is engaged and not be delayed until 90° of rod rotation have occurred. Therefore, we believe slack in the DNIPRO and PULS inner strap, just like that of the CAT, is suboptimal because delays in increasing tourniquet pressure are delays in stopping bleeding.

Limitations

Laboratory-setting limitations included: ideal application positions; calm, uninjured recipients; audible Doppler substitution for bleeding; good lighting; limited distractions; and a small group of calm, trained appliers. Recipients were a convenience sample recruited from friends, college students including male and female collegiate athletes, and college faculty. A major limitation regarding tourniquet wear is that applications were only as tight as needed for completion with no audible pulse and had upper pressure limits. Use under fire would likely involve worse application positions and therefore lower pre-tightening system pressures, requiring more windlass-rod turns just to reach "as tight as needed," and potentially tightening-system use to "as tight as possible," which means even more windlass-rod turns.

Conclusion

The SICH, DNIPRO, and PULS always reached completable arterial occlusion; the Y&B did not. No tourniquet became nonfunctional; however, Y&B stitching failures were concerning, particularly if multiple uses might occur. The Y&B also has significant design concerns: ease of clip bending, potential for losing slider-redirect-buckle pieces, many incorrect slider-redirect-buckle rethreading options, potential for windlass-rod removal, and inability to always secure the rod in the triangle.

Regarding tourniquets in general, 180°-turn, windlass-rod-tightening-system resolution routinely creates much higher than needed and much higher than desirable pressures at application completion, which probably matters with long tourniquet times. Additionally, hook-and-loop-limb-encircling straps of current tourniquets, including the CAT, are too short to engage base-area-strap-securing mechanisms on many adult thighs.

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Author Contributions

PW and CB contributed to concept development. All authors contributed to project design. All authors contributed to acquisition, analysis, and interpretation of data and drafting or revising of the article. All authors had final approval of the manuscript.

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