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Sweating the Little Things: Tourniquet Application Efficacy in Two Models of Pediatric Limb Circumference

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ABSTRACT Background: Current military recommendations include the use of tourniquets (TQ) in appropriate pediatric trauma patients. Although the utility of TQs has been well documented in adult patients, the efficacy of TQ application in pediatric patients is less clear. The current study attempted to identify physical constraints for TQ use in two simulated pediatric limb models. Methods: Five different TQ (Combat Application Tourniquet (CAT) Generation 6 and Generation 7, SOFTT (SOF Tactical Tourniquet), SOFTT-W (SOF Tactical Tourniquet – Wide), SWAT-T (Stretch Wrap and Tuck – Tourniquet) and a trauma dressing were evaluated in two simulated pediatric limb models. Model one employed four cardiopulmonary resuscitation (CPR) manikins simulating infant (Simulaids SaniBaby), 1 year (Gaumard HAL S3004), and 5 years (Laerdal Resusci Junior, Gaumard HAL S3005). Model two utilized polyvinyl chloride (PVC) piping with circumferences ranging from 4.25" to 16.5". Specific end-points included tightness of the TQ and ability to secure the windlass (where applicable). Results: In both models, the ability to successfully apply and secure the TQ depended upon the simulated limb circumference. In the 1-year-old CPR manikin, all windlass TQs failed to tighten on the upper extremity, while all TQs successfully tightened at the high leg and mid-thigh. With the exception of the CAT7 and the SOFTT-W at the mid-thigh, no windlass TQ was successfully tightened at any extremity location on the infant. The SWAT-T was successfully tightened over all sites of all CPR manikins except the infant. No windlass TQ was able to tighten on PVC pipe 5.75" circumference or smaller (age < 24 months upper extremity). All windlass TQs were tightened and secured on the 13.25" and 15.5" circumference PVC pipes (age 7–12 years lower extremity, age >13 years upper extremity). The SWAT-T was tightened on all PVC pipes. Discussion: The current study suggests that commercial windlass TQs can be applied to upper and lower extremities of children aged 5 years and older at the 50%th percentile for limb circumference. In younger children, windlass TQ efficacy is variable. Further study is required to better understand the limitations of TQs in the youngest children, and to determine actual hemorrhage control efficacy.

INTRODUCTION

In the USA, trauma is the leading cause of accidental injury death for individuals aged 5–24.[1] In patients who succumb to their injuries, hemorrhage remains the leading cause of possibly preventable death. Recent military data suggest that hemorrhage is responsible for 90.9% of potentially survivable combat deaths, with 67.3% of potentially survivable hemorrhage being truncal.[2] It is estimated that hemorrhage accounts for 35% of civilian prehospital trauma deaths, and 40% of deaths in the first 24 hours post-injury.[3]

In the latter half of the 20th century, the management of traumatic hemorrhage focused upon large volume crystalloid resuscitation, with little thought to hemorrhage control.[4] In recent years, the management of life-threatening extremity hemorrhage has focused upon the early use of tourniquets (TQ). The U.S. military experience unequivocally demonstrates the life-saving potential of TQ, especially when applied at the point of wounding and prior to the onset of shock.[5–8] This knowledge has increasingly migrated into the civilian EMS sector, culminating in the Stop The Bleed campaign.[9–11]

Modern commercial TQs were developed for and initially evaluated in the management of extremity hemorrhage in an adult population. Children have smaller limb circumferences and different blood vessel compliances. Although current military recommendations include the use of TQ in appropriate pediatric trauma patients, little data are available on pediatric TQ efficacy.[12,13] Lack of data on pediatric TQ use has been identified as a key civilian knowledge gap.[14] Prior to *in vivo* evaluation of TQ efficacy in pediatric patients, analysis in simulated models is required. The purpose of the current study was to identify structural design limitations present in commercially available TQs that might interfere with adequate hemorrhage control in two simulated pediatric limb models.

METHODS

Study Design

This was a descriptive analysis utilizing two simple models of simulated pediatric limb circumference. This study was

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Tourniquets

Four different commercially available windlass TQ (Combat Application Tourniquet Generation 6 and Generation 7 (CAT6, CAT7, C-A-T Resources, Rock Hill, SC), SOF Tactical Tourniquet and SOF Tactical Tourniquet-Wide (SOFTT, SOFTT-W, Tactical Medical Solutions, Anderson, NC), an elastic TQ (Stretch Wrap and Tuck Tourniquet (SWAT-T, TEMS Solutions, Abingdon, VA)) and a commercially available trauma pressure dressing (Emergency Trauma Dressing (ETD), Flat, 4", North American Rescue, LLC, Greer, SC), were evaluated during the current study.

Model One – Pediatric Resuscitation Manikin Model

A convenience sample of four commercially available pediatric resuscitation manikins representing an infant (Simulaids SaniBaby, Simulaids Inc, Saugerties, NY, USA), a 1-year old child (Gaumard HAL S3004, Gaumard, Scientific, Miami, FL, USA), and 5-year old child (Laerdal Resusci Junior, Laerdal, Stavanger, Norway; Gaumard HAL S3005, Gaumard, Scientific, Miami, FL, USA) were utilized in the study. Two 5-year-old child models were utilized to allow for potential anthropometric differences in different commercial products. Specific upper extremity TQ application sites, where anatomically feasible due to size constraints, included the proximal humerus, the mid-biceps area, and the mid-forearm. Lower extremity application sites included the proximal femur, the mid-thigh area and the mid-calf.

Model Two – PVC Pipe Model

Six segments of PVC piping with external circumferences ranging from 10.8 to 41.9 cm were purchased from a local hardware store (The Home Depot, Atlanta, GA, USA). Sizes were selected based upon those available for purchase. Anthropometric data on mean upper and lower limb circumference were used to determine equivalent age ranges for the PVC piping models.[15,16]

Tourniquet Application Success Criteria

Two different components were assessed for successful application: tightness of the TQ and ability to secure the windlass (where applicable). The ability to tighten the TQ strap around the limb without slack was graded as a pass (P). Slack was identified based upon the ability to easily slip more digits than an adult index finger beneath the TQ strap. The presence of a very small amount of slack removed by a single windlass revolution was classified as a windlass-enabled pass (*W*). Failure to remove slack with more than one windlass revolution was classified as a fail (*F*). Ability to secure the windlass (where applicable) was evaluated in a simple pass/fail (*P*/*F*) manner. If the TQ could not be tightened, the ability to secure the windlass was not assessed.

RESULTS

Manufacturing constraints related to the size of the stabilizing plates limited the minimum limb circumference for both the CAT and SOFTT brands of TQ (Fig. 1).

TABLE I. TQ Efficacy, Simulaids SaniBaby Infant Manikin Model

	Thigh	Calf	Mid-Biceps	Mid-Forearm
CAT7	W/P	F	F	F
CAT6	F	F	F	F
SOFTT	F	F	F	F
SOFTT-W	W/P	F	F	F
SWAT-T	F	F	F	F
ETD	F	F	F	F

P: Pass.
F: Fail.
W: Windlass-enabled pass.
1st Letter: Ability to tighten TQ.
2nd Letter: Ability to secure the windlass (where applicable).

FIGURE 1. Intrinsic minimum tourniquet circumference secondary to design limitation. Top: SOFT-T Tourniquet. Bottom: CAT Generation 7 Tourniquet.

FIGURE 2. Width limitation of elastic TQ in infant-sized manikin. Inherent size constraint of eleastic TQ results in crossing of joint line.

The results for the infant manikin are provided in Table I. With the exception of the mid thigh, all windlass-equipped TQs failed to tighten appropriately. Although the SWAT-T and the ETD were successfully tightened, they were classified as TQ failures because their width precluded the ability to isolate a specific location on the limb, with resultant risk of TQ application below the wound (Fig. 2).

Results for the 1-year old manikin are provided in Table II, while results for 5-year old manikins are provided in Tables III and IV. All TQ were able to be tightened in simulated proximal lower extremity in ages 1 year and older. Windlass-equipped TQs were unable to be tightened in the proximal upper extremity of the 1-year old manikin. Windlass-enabled successful TQ application was observed in the proximal upper extremity of the 5-year old manikins. Successful elastic TQ application was not limited by limb circumference, but rather limb length; the shorter the limb, the greater the likelihood of crossing either the elbow or knee joint, impairing efficacy.

Similar findings were noted for the PVC pipe model (Table V). TQs were more consistently successful on a simulated lower extremity equivalent than on an upper extremity equivalent. Even when successfully tightened, the smaller pipe diameters frequently prevented successful securing of the windlass.

DISCUSSION

Severe trauma remains a major public health threat, representing an estimated 12% of the global burden of disease.[3,17] Although anatomic location and situation are not provided, studies suggest that 30–40% of civilian trauma mortality is secondary to hemorrhage, with 33–56% of these deaths occurring in the prehospital environment.[3] Current military data suggest that 13.5% of possibly survivable hemorrhage involve isolated extremity wounds.[2] Based upon the U.S. military experience, TQs are increasingly recommended for the emergent management of exsanguinating extremity hemorrhage; these recommendations extend to pediatric patients.[5–7,10,11]

TABLE II. TQ Efficacy, Gaumard HAL S3004 1-Year-Old Manikin Model

	Thigh	Calf	Mid-Biceps	Forearm
CAT7	P/P	W/P	F	F
CAT6	P/P	W/P	F	F
SOFTT	P/P	F	F	F
SOFTT-W	P/P	F	F	F
SWAT-T	P	P	P	P
ETD	P	P	P	P

P: Pass.
F: Fail.
W: Windlass-enabled pass.
1st letter: Ability to tighten TQ.
2nd letter: Ability to secure the windlass (where applicable).

A retrospective study of trauma patients identified vascular injuries in 3.5% of 4,402 pediatric trauma patients treated at U.S. military hospitals.[13] Penetrating trauma was the mechanism of injury in 95.6% of cases, with 58.0% associated with blast injury. Upper extremity injury was noted in 28.1% of cases, while lower extremity injury occurred in 37.8%.

The efficacy of TQ application in children remains unclear. An orthopedic study demonstrated difficulty in TQ application for patients under 2 years of age.[18] In the study of pediatric vascular injuries, 6/112 (5.4%) patients had TQ applied, with 3 applied in the prehospital environment and 3 in the emergency department.[13] All three patients with field TQ application survived, although all three received primary or secondary amputation. This may reflect the significant injuries requiring prehospital TQ application. Of the two patients receiving ED TQ application who survived, neither required an amputation. However, this may reflect selection bias, in that the patients were sufficiently stable to survive to definitive care. No information on age or TQ location was provided.

A retrospective analysis of a military trauma registry identified 88 cases of pediatric TQ use between May 17, 2003 and December 25, 2009.[12] In the study, 81.8% of patients were male, with a mean age of 11 years, and a range of 4–17 years. The results of the study were similar to previous non-pediatric studies, suggesting that TQs were useful in this patient group. Unfortunately, no information was provided concerning location of injury (upper vs lower extremity) in relationship to age. Younger patients were more likely to die of wounds, but this finding was not significant. Additionally, the registry only captured hospitalized patients in whom TQs were applied. As such, patients who died in the prehospital environment after TQ failure, or those who presented without TQs after failure of prehospital application, would not have been captured in the study, thereby biasing the results.

In the civilian setting, pediatric TQ use is even more sparsely described. A single case report documents the application of a C-A-T TQ to the upper thigh of a 30 kg, 7-year old male after laceration of the femoral artery.[19] A 6-year-old male succumbed to a femoral artery bleed during a school shooting.[20] The specific location of the injury, and whether it was amenable to TQ application (ie extremity versus junctional), has not been reported. The lack of knowledge about pediatric TQ efficacy has been identified as a significant knowledge gap.[14]

The current study suggests that TQs may have some utility, but that this utility depends upon TQ type, patient age (as a surrogate for limb circumference), and limb location (upper versus lower, proximal versus distal). In the manikin model, TQs were successfully tightened when placed on the proximal lower extremity in the 1- and 5-year-old models. The fact that this location resulted in successful application suggests that a "high-and-tight" approach might be particularly beneficial in the pediatric population. A previous study demonstrated 100% TQ efficacy in an adult proximal thigh model.[21] Results on the upper extremity were mixed, even in

TABLE III. TQ Efficacy, Laerdal Resusci Junior 5-Year-Old Manikin Model

	High Leg	Mid-Thigh	Mid-Calf	Mid-Biceps	Mid-Forearm
CAT7	P/P	P/P	W/P	W/P	W/P
CAT6	P/P	P/P	W/P	W/P	W/P
SOFTT	P/P	P/P	P/P	P/P	W/P
SOFTT-W	P/P	P/P	W/P	P/P	F
SWAT-T	N/A*	P	P	P	P
ETD	N/A*	P	P	P	P

P: Pass.
F: Fail.
W: Windlass-enabled pass.
1st letter: Ability to tighten TQ.
2nd letter: Ability to secure the windlass (where applicable).
N/A*: Width of the elastic TQ resulted in placement in an area including both the high leg and the mid thigh.

TABLE IV. TQ Efficacy, Gaumard HAL S3005 5-Year-Old Manikin Model

	High Leg	Mid-Thigh	Mid-Calf	Mid-Biceps	Mid-Forearm
CAT7	P/P	P/P	W/P	W/P	F
CAT6	P/P	P/P	W/P	W/P	W/P
SOFTT	P/P	P/P	P/P	P/P	W/P
SOFTT-W	P/P	P/P	P/P	P/P	F
SWAT-T	NA*	P	P	P	P
ETD	NA*	P	P	P	P

P: Pass.
F: Fail.
W: Windlass-enabled pass.
1st letter: Ability to tighten TQ.
2nd letter: Ability to secure the windlass (where applicable).
N/A*: Width of the elastic TQ resulted in placement in an area including both the high leg and the mid thigh.

TABLE V. TQ Efficacy, PVC Pipe Model

PVC Circumference (CM)	Age (Mos) Equivalent UE	Age (Mos) Equivalent LE	CAT7	CAT6	SOFTT	SOFTT-W	SWAT-T	ETD
10.8	0–3	N/A	F	F	F	F	P	F
14.6	19–24	N/A	F	F	F	F	P	F
19.7	109–120	3–6	P/F	P/F	P/P	W/P	P	P
23.5	>156	10–12	P/F	P/F	P/P	W/P	P	P
33.7	>156	85–96	P/P	P/P	P/P	P/P	P	P
41.9	>156	133–144	P/P	P/P	P/P	P/P	P	P

P: Pass.
F: Fail.
W: Windlass-enabled pass.
UE: Upper extremity.
LE: Lower extremity.
1st Letter: Ability to tighten TQ.
2nd Letter: Ability to secure the windlass (where applicable).

the 5-year-old models. However, a pass or a windlass-enabled pass was possible in the upper arm of the 5-year-old models. The elastic TQs were more efficacious in smaller circumference locations when compared with windlass-TQs.

The PVC pipe model demonstrated similar findings. Smaller circumferences impeded TQ application. No windlass-TQ was successful when applied to PVC pipe simulating upper extremity, age <24 months. The smallest circumferences resulted in such sharp angles between the windlass and the constricting band that even if tightened, the TQ could not be secured. All windlass-TQs were successful when placed on PVC pipe equivalent to lower extremity, age >7 years.

In combat, windlass-TQ designs are preferred over elastic TQs, in part due to ease of use and ability for self-application and in part due to the mechanical advantage created by the windlass.[22] The two commonly fielded CoTCCC-approved TQs are both windlass-TQs. However, both of these TQs have a minimum effective circumference due to manufacturer design (Fig. 1). The use of elastic TQs may actually be more efficacious in pediatric patients, particularly smaller/younger patients, for several reasons. First, the design of elastic TQs permits more effective application on smaller circumferences. Second, pediatric patients have lower systolic blood pressures than adults, which may permit hemostasis with less applied force than large, muscular limbs encountered in combat soldiers.[18,23]

Limitations

The current study contains a number of limitations inherent to the nature of the study. Neither model was validated as a hemorrhage control simulator, and the PVC pipe model was particularly simplistic. The ability to tighten and secure a TQ is a simple and likely inadequate surrogate for in vivo ability to control extremity hemorrhage, especially when describing a windlass-enabled pass. A study on windlass-TQs demonstrated impaired TQ performance with any slack present.[24] While the inability to secure a TQ suggests a potential lack of clinical efficacy, the rigid nature of the PVC pipe may have artificially impaired this step.

The nature of pediatric adipose tissue and location of blood vessels may not permit adequate control even with a secured TQ. Alternatively, the lower mean systolic blood pressures noted in pediatric patients may actually improve TQ efficacy or permit the use of pressure dressings in wounds that would have required TQ application in adults. Further research is needed to study the physiology of hemorrhage control in this patient population.

The ages associated with the PVC pipe model were generated from anthropometric data representing idealized BMI data at the 50%. This may not accurately reflect modern western children, especially given the current childhood obesity epidemic.[25] Likewise, although developed to be realistic, the manikins represent an idealized body mass/size. Both models reflect a western bias, and may not adequately identify ethnic differences, particularly in places with child malnourishment and illness prone to conflict and therefore TQ need.

CONCLUSION

The current study suggests that commercial windlass-TQs can be applied to upper and lower extremities of children aged 5 years and older at the 50th percentile for limb circumference. In younger children, windlass TQ efficacy is variable. Elastic TQs were effective in all but the youngest age group, in which body size resulted in the TQ crossing joint lines. Further *in vivo* study is required to better understand the limitations of TQ in the youngest children and to determine actual hemorrhage control efficacy in all age groups.

PREVIOUS PRESENTATIONS

Portions of this manuscript were presented at the 2017 Military Health System Research Symposium, Kissimmee, FL, USA.

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REFERENCES

1. National Center for Injury Control and Prevention. 10 Leading Causes of Death, United States Highlighting Unintentional Injury Deaths, United States – 2105. Available at https://www.cdc.gov/injury/images/lc-charts/leading_causes_of_injury_deaths_unintentional_injury_2015_1050w760h.gif; accessed June 18, 2017.
2. Eastridge BJ, Mabry RL, Seguin P, et al: Death on the battlefield (2001–2011): implications for the future of combat casualty care. J Trauma Acute Care Surg 2012; 73: S431–7.
3. Kauvar DS, Lefering R, Wade CE: Impact of hemorrhage on trauma outcome: an overview of epidemiology, clinical presentations, and therapeutic considerations. J Trauma 2006; 60: S3–11.
4. Haut ER, Kalish BT, Cotton BA, et al: Prehospital intravenous fluid administration is associated with higher mortality in trauma patients: a National Trauma Data Bank analysis . Ann Surg 2011; 253: 371–8.
5. Kragh JF Jr, Dubick MA: Battlefield tourniquets: lessons learned in moving current care toward best care in an Army Medical Department at War. US Army Med Dep J 2016; 2: 29–36.
6. Kragh JF Jr, Dubick MA, Aden JK, et al: U.S. Military use of tourniquets from 2001 to 2010. Prehosp Emerg Care 2015; 19: 184–90.
7. Kotwal RS, Montgomery HR, Kotwal BM, et al: Eliminating preventable death on the battlefield. Arch Surg 2011; 146: 1350–8.
8. Kragh JF Jr, Littrel ML, Jones JA, et al: Battle casualty survival with emergency tourniquet use to stop limb bleeding. J Emerg Med 2011; 41: 590–7.
9. Kue RC, Dyer KS, Blansfield JS, Burke PA: Tourniquet use at the Boston Marathon. J Trauma Acute Care Surg 2015; 79: 701–2.
10. Goolsby C, Hunt RC, Goralnick E, et al: Stop the Bleed Education Consortium: education program content and delivery recommendations. J Trauma Acute Care Surg 2018; 84: 205–10.
11. Butler FK: Stop the bleed. Strategies to enhance survival in active shooter and intentional mass casualty events. The Hartford Consensus. A Major Step Forward in Translating Battlefield Trauma Care Advances to the Civilian Sector. J Spec Oper Med 2015; 15: 133–5.
12. Kragh JF Jr, Cooper A, Aden JK, et al: Survey of trauma registry on tourniquet use in pediatric war casualties. Pediatr Emerg Care 2012; 28: 1361–5.
13. Villamaria CY, Morrison JJ, Fitzpatrick CM, Cannon JW, Rasmussen TE: Wartime vascular injuries in the pediatric population of Iraq and Afghanistan: 2002–2011. J Ped Surg 2014; 49: 428–32.
14. Alix-Seguin L, Lode N, Orliaguet G, et al: Et Si Cetait des Enfants? Adaptation de la Prise en Charge Medicale en Cas d'Attentats Terroristes Avec de Nombreux Enfants Victimes. Arch Pediatr 2017; 24: 280–7.
15. De Onis M, Martines J, Onyango A, Pinol A, WHO Multicentre Growth Reference Study Group. Figure 28, Figure 30, Figure 39, Figure 41, WHO Child Growth Standards. Length/Height-for-Age, Weight-for-Age, Weight-for-Length, Weight-for-Height and Body Mass Index-for-Age: Methods and Development. World Health Organization 2006. Geneva, Switzerland.
16. Snyder RG, Spencer ML, Owings CL, Schneider LW Physical Characteristics of Children as Related to Death and Injury for Consumer

Product Safety Design. US Food and Drug Administration. UM-HSRI-BI-75-5 Final Report. PP 196–211. Silver Spring, MD. May 1975.

17. Peek-Asa C, Zwerling C, Stallones L: Acute traumatic injuries in rural populations. Am J Public Health 2004; 94: 1689–93.
18. Lieberman JR, Stahelli LT, Dales MC: Tourniquet pressures on pediatric patients: a clinical study. Orthopedics 1997; 20: 1143–7.
19. Callaway DW, Puciaty A, Robertson J, Hannon T, Fabiano SE: Case report: life saving application of commercial tourniquet in pediatric extremity hemorrhage. Prehosp Emerg Care 2017; 21: 786–8.
20. Alamasy S, Hassan C South Carolina School Shooting: 6-year-old Victim Dies. Cable News Network. October 2, 2016. http://www.cnn.com/2016/10/01/us/south-carolina-elementary-school-shooting-victim/index.html; accessed December 8, 2017.
21. Kragh JF Jr, Wallum TE, Aden JK 3rd, Dubick MA, Baer DG: Emergency tourniquet effectiveness in four positions on the proximal thigh. J Spec Oper Med 2014; 14: 26–9.
22. Altamirano MP, Kragh JF Jr, Aden JK 3rd, Dubick MA: Role of the Windlass in improvised tourniquet use on a manikin hemorrhage model. J Spec Oper Med 2015; 15: 42–6.
23. National High Blood Pressure Education Program Working Group on High Blood Pressure in Children and Adolescents: The fourth report on the diagnosis, evaluation, and treatment of high blood pressure in children and adolescents. Pediatr 2004; 114: 555–76.
24. Polston RW, Clumpner BR, Kragh JF Jr, Jones JA, Dubick MA, Baer DG: No slackers in tourniquet use to stop bleeding. J Spec Oper Med 2013; 13: 12–9.
25. Ogden CL, Carroll MD, Kit BK, Flegal KM: Prevalence of childhood and adult obesity in the United States, 2011–2012. JAMA 2014; 311: 806–14.