

An Evaluation of Two Tourniquet Systems for the Control of Prehospital Lower Limb Hemorrhage

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Background: Hemorrhage remains the main cause of preventable death on the modern battlefield. As Improvised Explosive Devices in Afghanistan become increasingly powerful, more proximal limb injuries occur. Significant concerns now exist about the ability of the windlass tourniquet to control distal hemorrhage after mid-thigh application. To evaluate the efficacy of the Combat Application Tourniquet (CAT) windlass tourniquet in comparison to the newer Emergency and Military Tourniquet (EMT) pneumatic tourniquet.

Methods: Serving soldiers were recruited from a military orthopedic outpatient clinic. Participants' demographics, blood pressure, and body mass index were recorded. Doppler ultrasound was used to identify the popliteal pulses bilaterally. The CAT was randomly self-applied by the participant at mid-thigh level, and the presence or absence of the popliteal pulse on Doppler was recorded. The process was repeated on the contralateral leg with the CAT now applied by a trained researcher. Finally, the EMT tourniquet was applied to the first leg and popliteal pulse change Doppler recorded again.

Results: A total of 25 patients were recruited with 1 participant excluded. The self-applied CAT occluded popliteal flow in only four subjects (16.6%). The CAT applied by a researcher occluded popliteal flow in two subjects (8.3%). The EMT prevented all popliteal flow in 18 subjects (75%). This was a statistically significant difference at $p < 0.001$ for CAT versus EMT.

Conclusion: This study demonstrates that the CAT tourniquet is ineffective in controlling arterial blood flow when applied at mid-thigh level. The EMT was successful in a significantly larger number of participants.

Key Words: Tourniquet, Hemorrhage, Amputation.

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“The fate of the wounded lays with those who apply the first dressing.”

Colonel Nicholas Senn, 1844–1908

Hemorrhage remains the leading cause of preventable mortality on the modern battlefield casualty.^{1,2} Advances in helmet and body armor design mean that increasing numbers of

soldiers are surviving blast and ballistic trauma with limb injuries that we would previously only have seen in the dead.^{3,4} The Improvised Explosive Device has become the signature weapon of our recent campaigns in Iraq and Afghanistan; traumatic amputation, the signature injury.⁵ As these Improvised Explosive Devices become increasingly powerful, more proximal injuries occur. Of particular concern is that limb injuries and traumatic amputations have become much more proximal.⁶

The training of our soldiers and military medical personnel, and the equipment issued to them, has undergone changes to reflect this. There is a much greater emphasis on the recognition and control of catastrophic hemorrhage.^{7,8} Limb destruction or traumatic amputation can result in fatal arterial hemorrhage. Pressure, novel hemostatic dressings, and tourniquets are all advocated by the military as life saving measures in exsanguinating battlefield extremity trauma. As such, all British and American soldiers on active duty in Afghanistan and Iraq are issued a windlass tourniquet, the Combat Application Tourniquet (CAT) (Phil Durango, LLC, Golden, CO, supplied by Fenton Pharmaceuticals, United Kingdom) to apply to themselves or an injured comrade immediately after traumatic limb injury.

Despite some initial success, real concerns now exist about the ability of these narrow windlass tourniquets to control hemorrhage when applied at mid-thigh level for proximal injuries.^{9–11} In 2009 and 2010, casualties have arrived in the Emergency Department with one, two, or even three, windlass tourniquets, high on the one extremity with persistent, active bleeding. Others have arrived with the bar on the windlass mechanism snapped, following further, futile attempts to tighten the tourniquet to arrest hemorrhage. The orthopedic community has a vast experience of pneumatic tourniquets for the control of intraoperative bleeding. Indeed, the average lower limb orthopedic surgeon will encounter >300 pneumatic tourniquet episodes per year.¹² Wide, pneumatic tourniquets can effectively and reliably control bleeding in the vast majority of cases.¹³ As a result of the above experiences, all limb trauma patients in the Field Hospital Emergency Department at Camp Bastion have their CATs converted to pneumatic operating theater tourniquets at the first opportunity, because once aggressive resuscitation begins, the limbs commonly begin to bleed profusely again, despite an in situ CAT (Fig. 1).

Clearly, prehospital tourniquets need to be small, light, robust, and fit for use in any environment. This explains our current reliance on windlass tourniquets. However, novel,

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Figure 1. An example of a traumatic above knee amputation with persistent hemorrhage despite a CAT tourniquet.



Figure 2. CAT (left) and EMT (right).

TABLE 1. Tourniquet Dimensions

	Dimensions (mm)	Volume (cm ³)	Weight (g)
CAT	175 × 50 × 32	280	59
EMT	127 × 70 × 64	569	220

small, and compact pneumatic tourniquets have been developed for prehospital use. One such device is the Emergency and Military Tourniquet (EMT; Delphi medical innovations, Vancouver, BC, Canada, supplied by Schuco International, London). Both devices are compact, light weight, and designed to easily be carried within personal equipment or prehospital first aid packs, as can be seen from Fig. 2, and the manufacturer supplied dimensions are given in Table 1.

Our hypothesis was that this pneumatic system would be more effective than a windlass system when applied at the mid-thigh level, as its design is more closely matched to those in civilian orthopedic practice. Our aim therefore was to evaluate whether the currently issued tourniquet was physically able to adequately occlude arterial flow when applied at mid-thigh level, first when self-applied and then when applied to the patient by a trained caregiver. A comparison

would then be made using the pneumatic EMT and subjected to statistical analysis.

METHODS

Prior approval for the study was gained from the local Research & Development and Ethics committees.^{14,15} Statistical support was gained for a power calculation derived from previously reported efficacy rates.^{9,16} This recommended a minimum of 24 participants to achieve significance. Patients attending the Senior Author's Military Elective Orthopaedic Outpatient Clinic in January and February 2010 were invited to participate in the study. All invited participants were currently serving military personnel. Each received a written explanation of the trial, its aims, risks, and the details of their participation. Written consent was gained from each participant.

A basic medical history was gained from participants aimed at excluding anyone at potential risk of complications from tourniquet application. The conditions in particular to be identified were a history of diabetes mellitus, hypertension requiring treatment, deep venous thrombosis, and arterial disease. In addition, those with active lower limb infection or lower limb surgery within the previous 6 weeks were identified. Anyone with a positive history of these conditions was then excluded from the study.

The participants' blood pressure, height, and weight were recorded and body mass index (BMI) was calculated prospectively to assess the impact these variables might have on the efficacy of the tourniquets. The popliteal arteries were then identified bilaterally using a handheld Doppler Ultrasound device (Dopplex, Model MD2; Huntleigh Healthcare, Cardiff, United Kingdom) by an independent medically trained team member. The two tourniquets to be investigated were the CAT, a windlass tourniquet, and the EMT, a pneumatic tourniquet. Both are CE* marked devices in widespread use in the worldwide military and prehospital care services.

A full explanation was given to each individual of how the windlass CAT tourniquet should be applied, as per the manufacturer's instructions and mandatory First Aid training for serving soldiers. Participants were then asked to apply it at the mid-thigh level. The participant chose at random as to which thigh the tourniquet was initially applied and tightened to the endpoint of the windlass mechanism or could be tightened no more. The Doppler was again used to evaluate arterial flow in the popliteal artery by the independent medical practitioner. The presence or absence of identifiable flow was recorded. The tourniquet was then applied to the other thigh, at the same level, by a separate member of the research party and again tightened as much as possible. The Doppler probe was again used to assess arterial flow in the popliteal artery; its presence or absence recorded and the tourniquet released. Finally, the pneumatic EMT tourniquet was applied to the first thigh and inflated by the lead researcher to a maximum pressure possible. The presence of the popliteal

*"Conformité Européenne"—manufacturer's declaration that the product complies with the essential requirements of the relevant European health, safety, and environmental protection legislation.

pulse was then recorded and the tourniquet deflated. Success was defined as the complete eradication of detectable popliteal blood flow on Doppler ultrasound. Any complications of the tourniquet application were recorded.

Statistical Analysis

The data were recorded on a paper proforma and transferred to a spreadsheet using Microsoft Excel 2003 (Microsoft, Seattle, WA), with no identifiable patient data recorded, thereby ensuring participant confidentiality. The results were analyzed using STATA version 7 (StatCorp LP, College Station, TX). The efficacies of each of the two modes of CAT tourniquet application, by the participant and by the researcher, were compared against one another, using Fisher's exact test. The efficacy of each mode of CAT application was compared with the EMT and all CAT applications combined were compared with the EMT using the McNemar chi-squared test.

In addition, we wanted to investigate the effect that systolic blood pressure and BMI had on the efficacy of the two tourniquets. The Wilcoxon rank-sum test was used to analyze the effects of both parameters. A p value < 0.05 was used to define statistical significance for all tests.

RESULTS

Forty consecutive patients were invited to participate in the study. Fifteen declined to participate. One volunteer was excluded because of recent lower limb surgery as per the predetermined exclusion criteria. A total of 24 participants were recruited. The mean age of participants was 36 years (range, 23–48 years). No complications after tourniquet application were reported by the participants. The self-applied CAT occluded popliteal flow in only four subjects (16.6%). The CAT applied by a researcher occluded popliteal flow in two subjects (8.3%). The EMT prevented popliteal flow in 18 subjects (75%; Table 2).

Statistical analysis comparing the efficacy of the two modes of CAT tourniquet application, the efficacy of each mode compared with the EMT and also all CAT applications combined compared with the EMT was performed. This analysis demonstrated statistical significance in the performance difference between the two tourniquets ($p = 0.001$), but not between the two applications of the CAT ($p = 0.25$).

Significant differences were also identified in the BMI and systolic blood pressures of those patients in whom the EMT failed when compared with those in whom it was successful. The average BMI in those in whom a CAT failed to control flow was found to be 27.4, when compared with 31.4 in those in whom the EMT failed (Table 3). Statistically analysis showed this difference to be significant at $p = 0.01$. The difference in the BMI of participants with successful or

TABLE 2. Success vs. Failure

	Success, n (%)	Failure, n (%)
CAT self	4 (16.7)	20 (83.3)
CAT other	2 (8.3)	22 (91.7)
EMT	18 (75)	6 (25)

TABLE 3. Average BMI by Tourniquet & Outcome

	EMT success	EMT failure
Average BMI	25.7	31.4
	CAT self-success	CAT self-failure
Average BMI	26.4	27.3
	CAT other success	CAT other failure
Average BMI	24.1	27.4

TABLE 4. Average Systolic Pressure by Tourniquet & Outcome

	EMT success	EMT failure
Average systolic (mm Hg)	122.7	134
	CAT self-success	CAT self-failure
Average systolic (mm Hg)	131	124.4
	CAT other success	CAT other failure
Average systolic (mm Hg)	115.5	126.3

failed attempts using the CAT tourniquet was not found to be significant in either the self-applied tourniquet or that applied by the researcher.

The average systolic pressure in those in whom a CAT failed to control flow was 125 mm Hg and for the EMT 134 mm Hg (Table 4). This difference in pressure was also shown to be statistically significant at $p = 0.04$. Again, the differences in systolic pressure of participants with successful or failed attempts with the CAT were not significant. Figures 3 and 4 demonstrate the relative BMI's and systolic pressures of participants with successful and unsuccessful applications of each tourniquet.

DISCUSSION

Tourniquets are known to have been used for the control of hemorrhage as far back as the ancient Greeks and are described as being used by military surgeons in the management of amputations in Roman times. Joseph Lister is credited with the first use of tourniquets for bloodless surgery in 1864, and Harvey Cushing developed a pneumatic tourniquet in 1904.¹⁷ Yet, well into the 21st century, debate still ensues about the efficacy and safety of tourniquet use in the control of traumatic hemorrhage.^{18–20} Historically, concerns have existed regarding the potential for morbidity from tourniquet application. In particular, these were centered on the potential for ischemic injury, infection, secondary compartment syndrome, and proximal amputation.²¹

Huge experience has been gained by military medical personnel in Iraq and Afghanistan since 2001, and the research in particular of Kragh et al.,^{10,22} has clearly demonstrated the life saving capacity of the appropriate use of tourniquets in the battlefield casualty, and in particular, the traumatic amputation. However, the majority of this experience, particularly in prehospital emergency management in Afghanistan, remains with the narrow windlass tourniquet.

The early work of Kragh et al.¹⁰ from Iraq in 2006 demonstrated the relative ineffectiveness of the CAT tourniquet in comparison with the pneumatic tourniquet. Their figures show that two or more tourniquets were required in 106

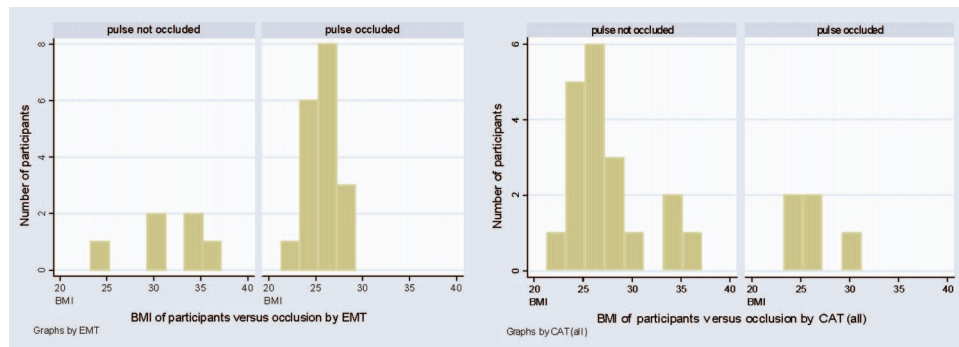


Figure 3. The effect of BMI on the efficacy of the tourniquets.

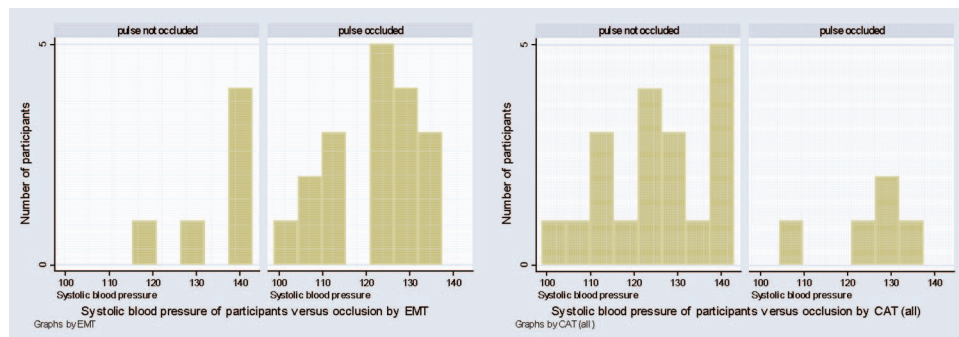


Figure 4. The effect of systolic blood pressure on the efficacy of the tourniquets.

of 309 limbs, and that the first tourniquet was effective in only 53% of cases. This figure is for both upper and lower extremities combined. They also demonstrated a lower efficacy when applied at mid thigh when compared with leg or arm.

The use of pneumatic tourniquets is entrenched in civilian surgical practice, with an estimated 15,000 uses daily around the world.¹⁷ It is widely accepted that a wider tourniquet allows better arterial occlusion, and at lower occlusion pressures.^{13,23,24} This improves efficacy as well as safety. The EMT can reach 300 mm Hg in bench testing, similar to those typically required to occlude arterial flow in clinical and perioperative practice.¹³ The EMT is also 90 mm wide, when compared with 40 mm for the CAT.

There have been surprisingly few scientific studies evaluating the efficacy of tourniquets in the controlled environment. Those that have been published, however, give conflicting opinions. Swan et al.²⁵ in 2009 used 10 volunteers with 3 different tourniquets at 4 different anatomic locations. They suggested that all three successfully occluded flow, but that there were “particular difficulties” in application above the knee. Wenke et al.¹⁶ studied a one-handed tourniquet designed for self-application that was being issued to United States service personnel. In 11 participants, the tourniquet was self-applied to the thigh and the popliteal pulse recorded. It was found to be effective in the upper limb. However, the tourniquet failed to occlude popliteal flow in all 11 participants when applied to at thigh level.

Walters et al.²⁶ then looked at a total of seven tourniquets, including the CAT and EMT. They looked at application at mid thigh and on the upper arm in 18 volunteers.

Although they found differing efficacies between the various devices when applied at mid thigh, they were able to report effective elimination of the popliteal pulse using Doppler ultrasound in 100% of volunteers with the CAT and EMT.

Finally, a Canadian study by King et al.⁹ performed in 2004 investigated 5 different tourniquet systems in 10 volunteers. They found that the proprietary one-handed tourniquet, when applied by another participant, failed to occlude distal flow in the lower limb in all cases, but that the EMT pneumatic tourniquet occluded flow in 80% of cases.

By simply comparing two tourniquets at one anatomic level, we have been able to clearly show a statistically significant difference in their efficacies. We have shown that the CAT is unable to prevent arterial flow when events necessitate a mid-thigh application. This study, in a controlled environment, has backed the clinical observations of those practicing in Iraq and Afghanistan up to the present day. In those in whom the EMT failed, we have been able to show that both BMI and systolic pressure were significantly higher. This may explain the failures in those minority of cases and adds further weight to our claim that the EMT is a more effective thigh tourniquet.

In our study, some concerns may exist regarding the inability of the participants in the study to tolerate the CAT tourniquet at a tightness required to occlude arterial blood flow. It is fair to say that in the fraught combat environment—the casualty or medic has the visible endpoint of cessation of bleeding as a guide. Some may feel that this could bias the study. However, the experience of the researchers was that discomfort was not the limiting factor in application. The

windlass mechanism of the latest model of CAT tourniquet currently in service has a clear limit to the distance of travel of ~30 mm. Even when correctly applied, this seemed insufficient to adequately constrict the thigh. This limit was invariably reached before discomfort precluded further tightening in our participants. This is backed by the presentation of casualties to Field Hospitals with broken windlass mechanisms from overtightening.

One other possible criticism of our method is that the operator of the Doppler ultrasound was not blinded from which tourniquet was in use. This was because the authors felt that the practical requirements to achieve this were such that they would significantly increase the duration of application of the tourniquet, thus increasing the level of discomfort and the risk of complications for the participants. Audible flow was clearly present when application failed, with no room for ambiguity.

Finally, it is not the recommendation of the authors that the EMT should replace the CAT for general issue to all front-line soldiers. Although the EMT is compact, light, and well packaged, it is not primarily designed as a self-application tourniquet and is not as durable as a CAT. However, the increased efficacy of the EMT suggests that it may be appropriate for it to be available to front-line medics, paramedics, and doctors within the military and civilian prehospital organizations, for use in those casualties with proximal injuries accompanied by life-threatening hemorrhage. Our study suggests that better hemorrhage control could be achieved using the EMT during extrication and transfer to the surgical facility.

CONCLUSION

This study clearly demonstrates that the CAT tourniquet is ineffective in controlling arterial blood flow when applied at mid-thigh level, whereas the EMT was successful in a significantly larger number of participants. By focusing on mid-thigh application, and the two tourniquets most commonly used, we have been able to demonstrate a clear statistically significant difference in the efficacies of the CAT and EMT tourniquets. This study has clear battlefield care implications.

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