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Mechanical Testing of Models of Tourniquet After Environmental Exposure

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Abstract:
The purpose of the present study was to mechanically assess models of emergency tourniquet after 18 months of environmental exposure to weather to better understand risk of component damage. Materials and Methods: An experiment was designed to test tourniquet performance on a manikin thigh. Three tourniquet models were assessed: Special Operations Forces Tactical Tourniquet Wide, Ratcheting Medical Tourniquet, and Combat Application Tourniquet. Unexposed tourniquets formed a control group stored in a laboratory; exposed tourniquets were placed outdoors on a metal roof for 18 months in San Antonio, Texas. Two users, a military cadet and a scientist, made 300 assessments in total. Assessment included major damage (yes–no), effectiveness (hemorrhage control, yes–no), casualty survival (alive–dead), time to stop bleeding, pressure, and blood loss. Time, pressure, and blood loss were reported in tests with effectiveness. Results: Exposed devices had worse results than unexposed devices for major damage (3% [4/150] versus 0% [0/150]; $p = .018$), effectiveness (89% versus 99%; $p = .002$), and survival of casualties (89% versus 100%; $p < .001$). In tests for effectiveness, exposed devices had worse results than unexposed devices for time to stop bleeding (29 seconds versus 26 seconds; $p = .01$) and pressure (200mmHg versus 204mmHg; $p = .03$, respectively), but blood loss volume did not differ significantly. Conclusion: Compared with unexposed control devices, environmentally exposed tourniquets had worse results in tests of component damage, effectiveness, and casualty survival.
Keywords: first aid; damage control; hemorrhage/prevention and control; shock; tourniquet; resuscitation; emergency medical services

Introduction:
Emergency tourniquet use to stop bleeding from limb wounds has changed since 2001 from a means of last resort to a means of first aid.1–3 Widespread fielding of tourniquets to deploying US Military Servicepersons since 2005 was made in tandem with their training.4 Many Servicepersons eventually became comfortable with tourniquets and wanted them nearby even to the point of routinely hanging tourniquets on the outside of their military uniform.5,6 This has been discouraged because it is outside the recommended place—inside the first aid kit, where, in a crisis, other people will look for tourniquets to use—and it exposed tourniquets to the environment. Experienced medics thought such exposure may cause problems, such as increased risk of damage to some components of the tourniquet. Subsequently, studies were performed to better understand this risk, but the specific type of exposure, such as heat, light, or humidity, that might increase risk of damage remained unknown.7–10 One study was made after exposure to a simulated summer in Baghdad, Iraq, for 91 days in an oven at 54°C, and its finding of no increased damage risk led us to consider environmental exposure that more closely simulates risk in the field, including diurnal variation of sunlight, temperature, and humidity. We also wanted a longer exposure, to improve the likelihood of detecting problems. The purpose of this study was to mechanically assess tourniquet models after prolonged environmental exposure to weather to better understand risk of component damage.

Materials and Methods:
This study was conducted under an approved protocol. The study group included environmentally exposed tourniquets; the control group consisted of similar but unexposed tourniquets. Exposure to the environment was made by placing the study group of tourniquets on the metal roof of a home in the center of San Antonio, Texas. The unexposed control group was stored in a climate-controlled laboratory. The two groups of tourniquets were purchased simultaneously from the same lots and batches and were concurrently exposed or stored. The exposure began 3 July 2013 and ended 2 January 2015 (i.e., 548 days, or 18 months). The three models of tourniquet studied were the Special Operations Forces Tactical Tourniquet in its wide version (SOFTT-W; Tactical Medical Solutions; https://www .tacmedsolutions.com), the Ratcheting Medical Tourniquet (RMT; M2 Inc.; http://www.ratchetingbuckles.com), and the Generation 6 version of the Combat Application Tourniquet (C-A-T; Composite Resources; https://www .narescue.com; Figure 1). C-A-T use was single-routed for the self-adhering band. There were two tourniquet users—a scientist (user 1) and a cadet (user 2). Users had familiarization training in use of the manikin and with each model of tourniquet. The cadet was an undergraduate student from the US Military Academy and had been formally trained in C-A-T use, whereas the scientist was a tourniquet expert and had tourniquet experience in trauma care, executive consultation, and research and development.

The scientist trained the student in the use of study tourniquets. Tourniquet training included reading the instructionsfor use, handling of each model, and one or two practice uses for each model on the manikin before testing began. A total of 300 tests (replicates) were performed—150 tests each in the control group and study group. A total of 30 tourniquet devices were used overall in the study, with five devices per model allocated to both the study and control groups (10 devices per model for the study overall). Each device was tested five times by each of the two users. Thus, both users performed 150 tests, 75 tests each in the control and study groups. The order in which the devices were tested was randomized such that the control group and study group were assessed concurrently. User order was one at a time and as allowed by the individual's schedule. The scientist performed the first test, the cadet (user 2) made the next 150 tests, and the scientist finished with his 149 remaining tests. The tourniquets were tested on a laboratory manikin that was designed to aid training by providing feedback on user performance. The investigators used a HapMed™ Leg Tourniquet Trainer (leg model 000F; CHI Systems; http://www.chisystems.com); a simulated right-thigh with an above-knee amputation injury was the testing scenario.10–13 The medial hip had an embedded computer with a smartphone-like touchpad. Software integral to the thigh (version 1.9; CHI Systems) allowed the manikin to stand alone and be operated by user input through finger touch on the pad. The thigh was placed on a laboratory table and was operated in accordance with the manufacturer's instructions. The proximal thigh circumference of the manikin is 57cm (22.25in), representing a medium build for the simulated casualty; software calculations allow simulation of small, medium, or large circumferences. Tourniquets, users, tests, and outcomes were uniquely identified. The manikin thigh did not bleed, but bleeding was represented by red lights that transilluminated the wound. The number of lights illuminated represented the bleeding rate: all 26 lights illuminated indicated uncontrolled bleeding, few lights blinking indicated intermediate control, and no lights illuminated indicated bleeding had stopped. Pressures near the threshold required for effectiveness may teeter at, above, and below the threshold in real time, just as in real patients; the lights may flicker on and off; and the screen may flicker bleeding– not bleeding (stable), which simulates care well if the tourniquet use is borderline between inadequate and adequate. During tourniquet application, rolling of the thigh on the ground or table can add a bit of extra pressure to the underlying compressed sensors or subtract a bit when the thigh rolls off the sensors. The manikin has piezo-electric transducers as pressure sensors under the 8mm-thick silicone skin of the manikin; sensors are arrayed in a line as a flexible strip of quarter-sized transducers, which run proximally to distally along the undersurface of the silicone skin where the underlying main artery is in anatomic specimens. A second similar strip is placed diametrically opposite on the thigh to the other strip to adequately sense pressure as an average under the tourniquet on both sides of the entire length of the thigh and from the proximal to distal edges of the tourniquet (or tourniquets, if more than one tourniquet is applied). The pressure amplitude is displayed as number (mmHg) on the manikin screen and is an average value sampled across sensors that are compressed at the time of sampling; sampling of pressure was made at the time of determination of bleeding control (i.e., when the button is pushed). Run-time feedback was on, so limited data during application were shown on the touch screen, including a bar graph of pressure, which was displayed as a short, black bar, indicating low pressure, or a long, green bar. Such feedback was moment to moment in real time when a pressure threshold was achieved in bleeding control; the software determined the threshold based on the amplitude of the average pressure applied during sampling, the width of the pressure sensed, and the limb circumference. The pressure is sensed in 1mmHg increments, and the device is recalibrated whenever refurbished. Pressure values do not become uncalibrated; there is no artefact such as a drift over time. Touchpad readouts for the results of each iteration included hemorrhage control, the time of application, the pressure exerted under the tourniquet, and the simulated blood loss volume. The measure of time to determination of hemorrhage control extended from the start of the iteration until the manikin detected that no more blood was lost; if the tourniquet broke, then the manikin could determine that hemorrhage control was not occurring. Effectiveness was determined by the cessation of blood loss (i.e., hemorrhage control). Iterations began with a tourniquet laid out flat and undone on the benchtop. Iterations ended when the user touched the touchpad button, determining that the hemorrhage was stopped. Users tightened tourniquets until they perceived that simulated bleeding stopped or until the casualty was dead. The setting was Care Under Fire, a setting resembling emergency care when under gunfire The manikin settings also included a constant simulated hemorrhage rate (625mL/min). At this rate, the bleedout time was 4 minutes (240 seconds); in the absence of any hemorrhage control, simulated death would occur at 240 seconds.

If partial hemorrhage control occurred, then longer survival could occur. The amount of bleeding required for the casualty status to turn from "bleeding" to "dead" was 2,500mL, half of the start value of 5,000mL. The touchpad reported simulated blood loss volume as calculated from arterial flow and number of pulses over time.
Results were summarized by outcome and by models of tourniquet. The primary outcome was effectiveness (yes– no, hemorrhage control). Secondary outcomes included casualty status (alive–dead), tourniquet breakage (yes– no; and by degree: major–minor), time to cessation of bleeding (seconds), pressure (mmHg) applied to the skin by the tourniquet to achieve hemorrhage control, and the calculated volume of simulated blood loss (mL). Effectiveness and pressure were measured by the manikin, while breakage and turn-click numbers were determined by the user. Major damage of a tourniquet device was catastrophic disruption of a component of the tourniquet such that it was unable to be made effective by the user. Collected data were used to calculate composite results of five other outcome measures: hemorrhage control, time to stop bleeding, total trial time (sum of time to stop bleeding, time to secure the tourniquet and assess its placement, and time to assess the casualty), the pressure exerted under the tourniquet, and the simulated blood loss volume. Composite results were determined in two ways. The first was a composite score for each test as a number, the count (0 to 5) of the five possible elements that were satisfactory (i.e., hemorrhage control was yes, the time of application was 60 seconds or less, the pressure was within 150mmHg and 300 mmHg inclusive, blood loss was less than 500mL, and major damage of any tourniquet component was absent). The second composite outcome was a binary "good" or "bad" result for each test of whether every element making up the composite result was satisfactory.
Additional results were calculations derived from existing data. "After-time" included time needed to secure the tourniquet, assess its placement, and assess response of the casualty to its use; after-time was calculated by subtracting time to stop bleeding from total trial time. During the data collection, both users recorded their own qualitative assessments of the models of tourniquet to supplement the quantitative assessments. Categorical data (i.e., hemorrhage control, casualty status, and damage in 2x2 contingency tables) were compared by exposure status (unexposed–exposed) with use of a Fisher exact test. Then a Cochran–Mantel–Haenszel test was used to see if such exposure effects were different among the three tourniquet models. Likelihood ratio p values were reported. Descriptive statistics were used to portray results.
Continuous data (e.g., time to stop bleed, pressure, blood loss) were summarized by mean ± standard error of the mean values and analyzed by using a mixed-model analysis of variance (ANOVA). Components within the statistical model, including the user as a random effect, were presented as a percentage for each continuous parameter to estimate their restricted maximal likelihood variance. Fixed-effect tests were made by exposure group, model of tourniquet, and groupxmodel interaction. Group means were compared by using a Tukey adjustment within the mixed model.
Additionally, if the tests of tourniquet failed to stop bleeding, the skewing of continuous data was known to be severe; for example, bleeding would only end upon the death of the casualty at 2,500mL, compared with 150mL routinely measured with success in bleeding control. Further skewing from nontreatment effects, such as the effect of the user, has been known by the investigators from their previous studies when users have different caregiving strategies, skill levels, or experience levels. Given this, a contingency was planned to analyze the subset of data that were reliable. The plan was as follows: if a test of tourniquet had a bad composition (i.e., the second composite outcome was a bad result), we then removed all such tests in which bleeding was not stopped (i.e., the subset analyzed had its tests with a result of composite = good) and a two-way mixed-model ANOVA was performed, with the user as a random effect in the statistical model to compare the continuous variables by exposure status (yes–no) by model of tourniquet. For pairwise comparison of categorical data of tourniquet models, a nonparametric Wilcoxon method was used. For pairwise comparison of means of tourniquet models, Student's t test was used to stratify results. Significance for results was established when values were $p < .05$. All statistical analysis was conducted by using SAS software (SAS Institute; http://www.sas.com) and MS Excel 2003 (Microsoft; www.microsoft.com).

Results

Overall Results

Of the 300 tourniquet tests, 256 had a good outcome in that the composite result had every component of the composite being satisfactory; 44 tests had a bad outcome in that one or more components of the composite result were unsatisfactory. From the analysis of continuous variables, these 44 test results were removed from the subset to be analyzed, but none was removed from overall analysis and from categorical data analysis.

Effectiveness Results by Tourniquet Model

The C-A-T's effectiveness percentage was 91% (91 of 100 tests); unexposed C-A-T devices had 100% effectiveness (50 of 50 tests), whereas exposed devices had 82% effectiveness (41 of 50 tests; p = .003). The RMT's effectiveness percentage was 98% (98 of 100 tests); unexposed RMT devices had 100% effectiveness (50 of 50 tests), whereas exposed devices had 96% effectiveness (48 of 50 tests; all p = .495). The SOFTT-W tourniquet's effectiveness percentage was 94% (94 of 100 tests); unexposed SOFTT-W devices had 98% effectiveness (49 of 50 tests); whereas exposed devices had 90% effectiveness (45 of 50; all p = .204). The Cochran–Mantel–Haenszel tests showed the C-A-T was significantly more susceptible to exposure than the RMT or SOFTT-W ($p \leq .001$).

Casualty Survival Results:

Overall and by Tourniquet Model

For the overall study, survival rate (alive–dead) was 95% (284 of 300); survival of casualties was 100% (150 of 150) when unexposed devices were used and 89% when the exposed devices were tested (134 of 150 tests; $p < .001$). The Cochran–Mantel–Haenszel tests showed the C-A-T was significantly more susceptible to exposure than the RMT or SOFTT-W ($p \leq 0.001$).

Major Damage Results:

Overall and by Tourniquet Model

For the overall study, major damage (yes–no) occurred in 1% of tests (4 of 300). Unexposed devices had 0% major damage, whereas exposed models had significantly more, at 3% (4 of 150 tests; p = .018). The Cochran–Mantel–Haenszel tests showed the C-A-T to be marginally, although significantly, more susceptible to exposure ($p = .044$).

Time to Stop Bleeding Results:

Overall and by Tourniquet Model

For the overall study, 14% of the variance of the time to stop bleeding results could be attributed to the user. Overall, the mean time to stop bleeding results for all three models of tourniquet was 47 seconds. However, these results included all 44 tourniquet tests that had a bad composite score. Excluding those 44 tests, the mean time to stop bleeding was 27 seconds; for unexposed devices, the mean was 26 seconds; and for exposed models, 29 seconds (p = .01). Results of mean time to stop bleeding by user were two tiered: user 1 (scientist) was slow (30 seconds) and user 2 (cadet) was fast (25 seconds; $p < .001$).

Results of time to stop bleeding by model of tourniquet were three tiered, with each model in its own tier. The C-A-T was fast, with a mean time of 21 seconds; the SOFTT-W was intermediate (mean, 29 seconds); and the RMT was slow (mean, 34 seconds). Each pairwise comparison differed significantly ($p < .001$, all three pairs). The respective mean times to stop bleeding for the unexposed and exposed tourniquets were as follows: C-A-T, 19 and 23 seconds; RMT, 33 and 35 seconds; and SOFTT-W, 26 and 29 seconds. Results of mean time by model and by exposure were five tiered. The slowest tier included exposed and unexposed RMT devices. The next--to-slowest tier included unexposed RMT devices and exposed SOFFT-W devices. The middle tier included exposed and unexposed SOFFT-W devices. The next-tofastest tier included unexposed SOFFT-W devices and exposed C-A-T devices. The fastest tier included unexposed C-A-T devices. Of 15 pairwise comparisons, only four were not significant: exposed and unexposed RMT, exposed and unexposed SOFTT-W, unexposed SOFTTW and exposed C-A-T, and unexposed RMT and unexposed SOFTT-W ($p \geq .056$, all four pairs).

Total Trial Time Results:

Overall and by Tourniquet Model For the overall study, 9% of the variance of the total trial time results (i.e., sum of time to stop bleeding, time to secure the tourniquet and assess its placement, and time to assess the casualty) could be attributed to the users.

Results of mean total time by user were two tiered:

user 1 (scientist) was slow (43 seconds) and user 2 (cadet) was fast (37 seconds; $p \leq .001$). Among the 256 effective tests, the mean total time results for all three models of tourniquet was 39 seconds; for unexposed

devices, 38 seconds; and 43 seconds for exposed models (p = .003). Results of total time by tourniquet model were three tiered, with each model in its own tier. The C-A-T was fast (mean, 33 seconds), the RMT was intermediate (mean, 41 seconds), and the SOFTT-W was slow (mean, 46 seconds). Each pairwise comparison differed significantly (p ≤ .048, all three pairs).

After-Time Results:

Overall and by Tourniquet Model

For the overall study, 9% of the variance of the aftertime (i.e., total trial time minus time to stop bleeding) results could be attributed to the users. Among the 256 effective tests, the mean of the after-time results for all three tourniquet models was 12 seconds; unexposed devices had a mean of 11 seconds, and the mean of the exposed models was 14 seconds (p = .04). Results of after-time by tourniquet model were three tiered, with each model in its own tier. The RMT was fast (mean, 8 seconds), the C-A-T was intermediate (mean, 12 seconds), and the SOFTT-W was slow (mean, 18 seconds). The order of after-time results was the same as time to stop bleeding except the RMT was first instead of last. Each pairwise comparison differed significantly (p < .001, all three pairs; Figure 2). The 0.08-second difference in mean after-time between users was not significant (p = .80).

Pressure Results:

Overall and by Tourniquet Model For the overall study, 21% of the variance of the pressure results could be attributed to the users. Among the 256 effective tests, the mean pressure results for all three tourniquet models was 203mmHg; unexposed devices had a mean of 204mmHg, and the mean of the exposed models was 200mmHg (p = .03). Results of pressure by tourniquet model were two tiered: the C-A-T and SOFTT-W were in the high tier, with means of 206 mmHg and 204mmHg, respectively; RMT was in the low tier at 198mmHg. In pairwise comparison, the C-A-T and RMT pair and the SOFTT-W and RMT pair differed significantly (p = .0008 and .02, respectively). Results of mean pressure by user were two tiered: user 1 (scientist) was low (197mmHg) and user 2 (cadet) was high (208mmHg). The 9mmHg difference in mean pressure between users was significant (p < .001). Blood Loss:

Results Overall and by Tourniquet Model

For the overall study, 50% of the variance of the blood loss volume results could be attributed to the users. Among the 256 effective tests, the mean blood loss for all three tourniquet models was 163mL. There was no significant difference between unexposed and exposed devices in mean blood loss, which were 162mL and 173mL for unexposed and exposed devices, respectively (p = .15). Results of blood loss by tourniquet model were three tiered, with each model in its own tier. The C-A-T was low (mean, 126mL), the SOFTT-W was intermediate (mean, 155mL), and the RMT was high (mean, 221mL). All three pairwise comparisons were significant (p < .001, all three pairs; Figure 3). Results of mean blood loss by user were two tiered: user 2 (cadet) was low (128mL) and user 1 (scientist) was high (207mL). The 79mL difference in mean blood loss between users was significant (p < .001; Figure 4). The respective mean volumes of blood loss with the unexposed and exposed tourniquets were as follows: C-A-T, 112mL and 140mL; SOFTT-W, 152mL and 159mL; and RMT, 223mL and 219mL. Results of mean blood loss by model and by exposure were three tiered. The high tier included unexposed and exposed RMT devices. The middle tier included exposed and unexposed SOFTT-W, and exposed C-A-T devices. The low tier included unexposed C-A-T devices. Of 15 pairwise comparisons, only four were not significant: exposed SOFTT-W and exposed C-A-T, unexposed SOFTT-W and exposed C-A-T, exposed and unexposed SOFTT-W, and exposed and unexposed RMT (p ≥ 0.149, all four pairs).

Discussion:

The main finding of this study was that unexposed devices had significantly better performance than exposed devices in terms of effectiveness and survival of casualties. Furthermore, unexposed devices had less damage than exposed devices. The power of the exposure effect was also seen even if the test of a tourniquet did not fail, because the results still showed a strongly negative effect of exposure on other measures of tourniquet function. The study results were fairly consistent across the various parameters measured, with big differences by exposure status.

The exposure–dysfunction relationship's temporal nature, in that the cart came after the horse, also included its duration: the long duration made the gradient of response large by allowing longer exposure than previous studies, thereby allowing more damage and dysfunction to accrue and thus be detected. On the black nylon band, for example, the dark outline of the overlying windlass was left shadow-like while surrounding nylon was grayed. The specificity (outline size and shape, and its location underlying an object of similar size and shape) of the outline on exposed tourniquets indicated that sunlight (responsible components of such light need not be visible) caused this visible effect, which may be linked mechanically with the mechanism of failure, as outlined next. Altogether, this study offers evidence that environmental degradation of exposed tourniquets appears most obviously associated with a specific mechanism: sunlight, but interactions among different types of exposure may also occur. The medics in the field thought that exposure risked tourniquet damage, and the main finding of our study indicates this is true. The minor finding of this study is that the user effect on the results was substantial. The user explained a portion of the variance of the statistical model for the parameters measured and ranged from a minimum of 9% for both total trial time and after-time to a maximum of 50% for blood loss volume. Such a finding of user effects, which can be large, adds to a growing body of knowledge that optimal performance in tourniquet use requires optimal performance of the tourniquet user. This implies that the need for user development is a research priority; future studies may present opportunities to improve outcomes of tourniquet application. Our findings are coherent with established knowledge from fields like materials science, which has shown a specific causal link between ultraviolet (UV) light exposure and degradation of polymers like nylon. Although the preliminary nature of our study does not confirm such a mechanism, a brief review of relevant science may fill gaps in awareness of such science for the prehospital medical community. Specific mechanisms of breakdown of the nylon polymer are well known in materials science and include photodegradation. To address vulnerability to light, nylon molecules can be UV hardened, and UV-hardened nylon is common in such things as outdoor sporting equipment.14 Consumers and manufacturers, if they know about a need to mitigate risk of exposure, can request that the nylon components be UV hardened, and such a capability of nylon has been in the marketplace for decades. Manufacturers of outdoor sporting equipment, such as the maker of the RMT, are often familiar with the need to UV harden components such as nylon, whereas medical device makers who routinely make hospital items (i.e., indoor equipment) may not be. The RMT maker has tourniquet ratchet sales but also has their ratchets used with outdoor sporting goods, such as for snowboard bindings (M. Moran, personal communication). In our experiment, the strength, consistency, specificity, temporality, and coherence of the exposure-dysfunction association indicate it may be a cause–effect relationship. To briefly review relevant science, most goods made of a plastic material are formed by methods such as extrusion, injection molding, or extrusion blowing, which result in heat and high shear within the polymer as it is made into the desired form. These methods introduce impurities and reaction products, which make the goods susceptible to photodegradation and loss of mechanical integrity. The loss of strength, impact resistance, and mechanical integrity of plastics exposed to such things as UV radiation is well studied and leads to accelerated aging and embrittlement, but the types and locations (e.g., surface versus interior) of such material changes vary by the type of exposure (e.g., humidity, smog, ozone, or heat).14 Such changes in material properties reflect molecular alterations of the polymer chain (e.g., scission and cross-linking) as a result of photodegradation and can be assessed by measuring changes in physical traits of the polymer.16 Environmental stress cracking of polymers is established as a common cause of mechanical failure of devices made of polymer components, and when a fluid such as water enters the cracks during mechanical loading, the fluid acts locally in stressed regions, giving rise to small cracks known as crazes and, eventually, if the fluid remains present and the stress continues, to propagation of existing cracks or even to a catastrophic failure of the structure stressed. UV light has been shown to degrade resistance of polymers to stress cracking by worsening both the surface cracking and the mechanical properties of the polymer. Such degradation is worsened during high mechanical stress, and photodegradation may be synergistic with stress cracking. Environmental stress cracking in materials like polymers has been associated with device failure. Crazes can form at the tips of brittle cracks without environmental exposure, but environmental exposure may accelerate the process, leading to crack growth (in width, length, displacement, or ramification into a network) during mechanical stress. This may be little known among medical caregivers. The findings of this study are in the context of San Antonio's environment. Air quality in this location has been measured as good on 98% of days,19 and the studied exposure was similar to those in San Antonio in years past. For example, the concentration of ozone was 0.087 ppm during the exposure period, and this level has been San Antonio's average since 1993.20 That level of

of ozone, a highly corrosive air pollutant, ranks San Antonio as 39 of 50—among the worst of large cities in America. Ozone exposure can degrade the material strength of plastics, nylon, natural rubbers, and elastomers, and such materials have been recommended to be avoided in applications where ozone is present, because of the risk of corrosion and cracking. Ozone fades the dyes in nylon. Nitrogen dioxide has a notorious record of fading dyes in acetate, triacetate, viscose rayon, and cotton materials and has caused yellowing in white blends of acetate and nylon.21 San Antonio's clear-sky UV light index (0–15 scale) averages 6.755, a high value, whereas the US average is 4.9, a moderate value. In 2014, for example, monthly averages for UV exposure ranged from 2.94, a low value in December, to 10.63, a very high value in July; daily values ranged from 0 to 11 in 2014; 11 is an extreme value.20 The UV values in 2014 for San Antonio were similar to those of 2011 to 2013.20 Although materials may seem reasonably resistant to any one pollutant, the combined action of several pollutants can alter the materials. For example, when polyethylene, polypropylene, polystyrene, polyvinyl chloride, polyacrylonitrile, butyl rubber, and nylon were exposed to a mixture of sulfur dioxide, nitrogen dioxide, and ozone, the materials each sustained deterioration in strength.21 The negative interactions among individual types of exposure, such as sunlight and bird droppings, which contain corrosive uric acid, are not fully understood scientifically.

Recommendations based on the findings of the present study include:

- Tourniquets are best stowed in first aid kits as is a current practice by doctrine.
- Treat a tourniquet like a lifesaving medical device, not like a pen or pedometer.
- Users wearing tourniquets outside of uniforms or exposed otherwise should be made aware of the risks of degradation by efforts toward education, training, and policies.
- If tourniquets must be exposed, the duration of exposure should be minimized.
- If tourniquets must be exposed, the intensity of exposure should be minimized.
- If tourniquets are exposed, a person should be trained in assessing for damage.
- Exposed tourniquets may be replaced but criteria are unclear unless damage is extreme.
- An 18-month exposure as studied is too long so such tourniquets should be replaced.

Environmental exposure should be assessed if it may become a research priority, and the relevant skill sets of investigators may need determination to optimize funding mechanisms.

The limitations of this study are rooted in its design as a laboratory experiment. The way the investigators tested included the ability of the user to decide whether to attempt to improvise with broken tourniquets, in that if a tourniquet broke, the user could choose to attempt to gain effective control of bleeding by improvising techniques with use of the tourniquet in its damaged state. This improvisation occurred, but only with user 1 (scientist), the more experienced user, who conducted most of his tests after user 2 (cadet), so the devices tested by user 1 had previous wear and tear from the first test. The very first test by user 1 led to no breakage, but the second test did result in breakage for some devices, and so the proportion of tests with improvisation was higher for user 1. User 1, thus, took more time and had longer durations with partial hemorrhage control for the prolonged efforts in trial and error to find a way to make broken tourniquets work. Occasional effectiveness with improvisation led to higher blood loss volumes and longer times, and ineffectiveness eventually led to casualty death by exsanguination. Previously, we had not run across the need for such improvisation, but user 1 acquired more ability to control bleeding as he accrued more experience, and was better able to simulate caregiving by continuing efforts to save a life. In the past, the user, after repeated failures, terminated the test because of persistent futility. An unexpected usefulness of this limitation was its illustration of exsanguination death by the manikin, which occurred at 2,500mL blood loss, a 50% loss, and such simulation may help caregivers better learn the amount of time needed to attain bleeding control. If a fixed application procedure had been followed without improvising, results could have led to higher percentages of failure of tests and devices, and of deaths. In summary, compared with unexposed control devices, exposed tourniquets had worse results, including higher percentages of tests with component damage, ineffectiveness, and simulated casualty death.

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