Effects of Donning and Wearing Personal Protective Equipment on Tourniquet Use and Conversion

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ABSTRACT

Background: We sought to gather data about the effects of personal protective equipment (PPE) use on tourniquet interventions by preliminarily developing a way to simulate delay effects, particularly on time and blood loss. Such knowledge might aid readiness. Field calls to emergency departments may indicate donning of PPE before patient arrival. The purpose of this study was to investigate (1) delay effects of donning the PPE studied on field-tourniquet control of hemorrhage and (2) delay effects of wearing the PPE on application of a field tourniquet and its conversion to a pneumatic tourniquet. **Methods:** The experiment simulated 30 tests of nonpneumatic field tourniquet use (http://www.combattourniquet.com/wp-content). The research intervention was the use of PPE. Data were grouped. The control group had no PPE (PPE0). PPE1 and PPE2 groups had mostly improvised and off-the-shelf equipment, respectively. PPE1 included donning a coat, goggles, face covering, cap, booties, and gloves. PPE2 had analogous items. The group order was randomized. A test included paired trials: field tourniquet, followed by conversion. An investigator simulated the caregiver. A task trainer simulated a thigh amputation. Donning delays were evaluated as differences in mean times to stop bleeding compared with PPE0. Blood loss results from donning PPE were calculated as the delay multiplied by its bleeding rate, 500mL/min. **Results:** PPE0 had no delay: its mean blood loss was 392mL. PPE1 had 805mL more blood loss than PPE0 did. PPE2 exceeded PPE0 by 1004mL. Donning time (blood loss) for PPE1 and PPE2 were 1.4 minutes (712mL) and 1.7 minutes (863mL), respectively. The wearing of PPE did not slow down field tourniquet application or its conversion. **Conclusions:** How long it took to don PPE delayed the time to stop bleeding and increased blood loss, but wearing PPE slowed down neither field tourniquet application nor its conversion.

KEYWORDS: *bleeding control and prevention; precautions; emergency; simulation; readiness practices; device removal*

Introduction

Since 2000, the use of tourniquets to control limb-wound bleeding has increased.[1–3] A little-studied tourniquet topic is its use in concert with wearing PPE. PPE is commonly used in caregiving settings such as physicians' offices, clinical laboratories, and emergency departments. PPE may include clothing, gloves, goggles, face shields, or other equipment designed to protect the wearer from injury, illness, or spread of infection. PPE recommendations vary by circumstance, as in flu seasons, at accident scenes, or in medical procedures.

This study occurred in a 2020 pandemic of COVID-19, a human disease caused by the novel coronavirus 2019 (2019-nCoV, now referred to as SARS-CoV-2). We sought to develop caregiving concepts by simulating trauma during a pandemic. For military healthcare providers, training includes an Emergency Preparedness Response Course for treating casualties during an all-hazards incident.[4] The course content notes that "performance of even routine tasks may be affected while wearing personal protective equipment" because "tasks are accomplished more slowly" and "reaction and decision times are longer." If emergencies arise unexpectedly or calls lack information, field medics may face whether to don PPE as someone bleeds. Delays can result from donning gloves[5]; unwrapping a packaged tourniquet[6,7]; searching, finding, and grasping tourniquets from where they are kept[8]; additional routing of a band through its buckle[9]; and calling emergency services such as 9-1-1.[10] In two such simulations, 80%[6] and 86%[10] of the blood loss occurred before the tourniquet touched the patient.

Given little data of donning PPE for tourniquet application and conversion, we designed a way to simulate interventions to assess delay effects. The purpose of this study was to investigate (1) effects of donning the PPE studied upon control of bleeding and (2) effects of wearing the PPE on application of a field tourniquet and its conversion to a pneumatic tourniquet.

Methods

This experiment was conducted on 20 April 2020. The actions of interest were emergency-use of a field tourniquet and conversion of that tourniquet to a pneumatic tourniquet. The caregiver conditions were no PPE (PPE0), improvised PPE (PPE1), and off-the-shelf PPE (PPE2). There were 10 blocks of the three PPE conditions with condition order randomized by lot.

The first author (JFK), who is a clinician-scientist experienced with tourniquet and conversion procedures, performed the

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tests and collected the data. The patient was brought to the caregiver at an area that was set up for initial emergency treatment. The caregiver wore eyeglasses, scrubs, and medical rubber shoes. Prior to tests, the caregiver wore no PPE, and the equipment was shelved.

Conditions in the PPE1 group included donning a physician's coat, safety goggles, a bandana face covering (with two rubber bands), a fleece cap, a pair of plastic booties, and a pair of food-preparation gloves. Conditions in the PPE2 group included donning a disposable lab coat, a blue surgical mask, a blue surgical hat, a pair of plastic booties, a face shield, and a pair of treatment gloves. The face shield was improvised from duct tape, a large bandana, and a clear plastic sheet. This bandana was worn like a crown, and the sheet was taped to it to hang down. The coats were donned reversed. PPE was reused except gloves.

Although the field tourniquet instructions (http://www.combattourniquet.com/wp-content) do not address conversion, it was used accordingly, except in reuse and pulse and bleeding checks performed earlier to speed troubleshooting. Tourniquet conversion was from the nonpneumatic windlass model to a pneumatic model that was reused among tests (Emergency and Military Tourniquet [EMT]; Delfi Medical Innovations). Although its instructions do not address conversion, it was used accordingly (http://www.delfimedical.com/emergency-military-tourniquet/). A marker was used to record the time of tourniquet application.

Tests were divided into halves, referred to as trials. A trial of field tourniquet use preceded its paired trial of conversion of the field tourniquet to a pneumatic tourniquet. The test step order included any PPE donning followed by the paired trials (Table 1). Data were collected after the trials. Recording data between trials mimicked the period in which healthcare workers tend to their recordkeeping and make a decision to convert.

TABLE 1 *Test Procedures in the Control Group*

1	Begin a test time by starting a stopwatch. Step up to a manikin.
2	Begin a field tourniquet trial time by starting the manikin: bleeding is to be controlled.
3	Walk to a shelf. Find a first-aid kit. Unzip the kit open. Find and grasp a field tourniquet.
4	Carry the tourniquet and walk back to patient (manikin).
5	Apply the field tourniquet: tear a wrapper off the tourniquet. Put the wrapper aside.
6	Grip the folded loop in the self-adhering band with both hands.
7	Pull the folded loop apart to unfasten the band's Velcro surfaces. The loop is widely open.
8	Lift the wound-end of the limb. Pass the opened loop around the end of the limb.
9	Place the tourniquet 2–3 inches above the wound. Set the limb back down onto the gurney.
10	Pull the red tip of the self-adhering band to peel back its top layer off the bottom layer.
11	Cross nondominant thumb over band near buckle. Put fingers on skin nearby. Stabilize limb.
12	Grasp the running end of the band with the dominant hand.
13	Align hands to push-pull diametrically opposite in-line with the center of the encircled limb.
14	Push more with nondominant hand than the dominant hand pulls to still the limb on gurney.
15	Pull the band tightly to pull snug the band portion that is still looped around limb.
16	Secure the running end of band to its portion still looped around limb. Do not cover clips.
17	Turn rod to make the tourniquet compress the limb. Turns are to stop the external bleeding.
18	Finish the final turn of the rod. Secure the rod by putting an end into a clip.
19	Look at the wound for bleeding while feeling behind the distal thigh for an artery pulse.
20	Troubleshoot if pulse is felt or bleeding is seen. Troubleshoot until both are stopped.
21	Put any excess of the running end of the band between the clips.
22	Pull the time strap to bridge from one clip to the other. Fasten Velcro to lock the rod in.
23	Tape over the strap. Uncap marker. Write the time of day onto tape. Recap. Drop marker.
24	Stop manikin to end timing of field tourniquet trial. Lap stopwatch. Record data of trial.
25	Enter manikin scenario for emergency care and start manikin for a conversion trial.
26	Walk to the shelf to find and fetch a pneumatic tourniquet. Carry it and walk back to patient.
27	Open the packaged pneumatic tourniquet and set aside its instruction booklet and wrapper.
28	Unroll the tourniquet. Hold clamp handle to dangle open the loop in the band (bladder).
29	Pass the loop around the limb to place the pneumatic tourniquet above the field tourniquet.
30	Pull the tape off the field tourniquet, undo its strap, unclip rod, and undo the turns in the rod.
31	Peel back red tip of the self-adhering band to unfasten its Velcro until reaching the buckle.
32	Loosen the loop in the band. Pass loop off the limb to remove field tourniquet. Set it aside.
33	Slide the loop in the pneumatic tourniquet to place it 2–3 inches above the wound.
34	Set the clamp to the limb so the handles stand up on the loop encircling the limb.
35	Pull the running end of the band away from the limb so the loop encircles the limb snugly.
36	Pull the band lastly toward the D-shaped handle to improve snugness.
37	Squeeze the two handles together to shut the clamp and thereby close the bladder.
38	Squeeze the hand bulb to force its air into the bladder. After squeezing, let air refill the bulb.
39	Repeat squeezes to inflate bladder to compress the limb until wound bleeding is stopped.
40	Roll and stow the running end of the band. This is the portion not encircling the limb.
41	Put tape on band. Uncap marker. Write time of day onto the tape. Recap and drop marker.
42	Stop manikin to end conversion trial time.
43	Stop stopwatch to end test time. Record data of trial and test.

A patient manikin was used as described elsewhere.[11] Briefly, the HapMed Leg Tourniquet Trainer (CHI Systems, http://www.chisystems.com) simulated a thigh amputation. The scenario for tourniquet application and its conversion included a single adult with a medium build, field caregiving, and a

bleed-to-death time of 300 seconds. The rate fell into three levels: uncontrolled, partly controlled during mechanical application of a tourniquet, and controlled when an application succeeded. The manikin was laid supine on a bed sheet at gurney height atop two footlockers stacked atop a flatbed cart.

The manikin autonomously measured times (time to stop bleeding and trial time). It determined patient status (bleeding or stable), trial status ("go" [satisfactory] or not), tourniquet placement (good or incorrect), pressure (in mmHg and category [good or loose]), and blood loss. The caregiver collected ease-of-use data (1, very difficult; 2, difficult; 3, neutral; 4, easy; or 5, very easy) and test times (start, end, time of day). Donning time was not measured directly but occurred in the tourniquet trial during the time to stop bleeding. Donning delay times were separately calculated as differences in mean times to stop bleeding compared with the control group. Each test had a moment in both trials when bleeding was controlled, and the time periods thereafter within a trial were called tourniquet trial posttime or conversion trial posttime. The caregiver assessed bleeding control and secured the tourniquet during these periods. Other calculations included posttime (trial time minus time to stop bleeding) and test blood loss (sum of tourniquet trial and its conversion trial). Test number, a surrogate of accrued healthcare experience, assessed test time. The data collection time (test time minus the sum of its trial times) was a surrogate of healthcare recordkeeping.

Descriptive statistics were used to portray results (Excel 2003; www.microsoft.com). Analyses were performed using SAS, v. 9.4 (SAS Institute; www.sas.com). Continuous variables were tested for normality. Normally distributed data were presented as mean ± standard deviation (SD), and analysis of variance was used with the *F* test to assess mean differences among groups, followed by pairwise comparisons with post hoc Bonferroni correction. Non-normally distributed data were presented as median and interquartile ranges. Nonparametric methods for testing whether samples originated from the same distribution were used. The Kruskal-Wallis test by ranks was used for comparing the groups for time data, followed by a Mann-Whitney test for post hoc comparisons. A coefficient of determination, denoted as r^2, was used as the portion of the variance in the dependent variable that was predictable from the independent variable. Significance was determined at the two-sided $P < .05$ level.

Results

Test Results

The first test time lasted 6.0 minutes. On average, test times did not change significantly [in a power law of practice: test time = $6.0863 \times (\text{test number})^{-0.026}$; $r^2 = 0.0135$]. Test blood loss averaged 1462 ± 554.5mL and ranged from a minimum of 624mL to a maximum of 2391mL.

Trials of Tourniquet Application and Conversion

In field tourniquet trials, results showed that all 30 uses were effective in bleeding control to stabilize the patient. Field tourniquets were placed correctly in 28 of 30 uses and incorrectly twice. Pressures applied by tourniquets were sufficient in 29 uses and loose in 1. Overall, there were satisfactory results in 28 uses, with 2 unsatisfactory results involving incorrect placement both times, compounded by insufficient pressure in 1 case. The mean pressure and blood loss were 387 ± 66.6mmHg and 995 ± 479.6mL, respectively. The mean field tourniquet trial time was 2.8 ± 0.9 minute (Table 2). Ease of use in field tourniquet trials was either 4 or 5, with a median of 4.

TABLE 2 *Mean Results of Trials*

Trial Type	Trial Time, min*	Time to Stop Bleeding, min*	Pressure, mmHg*	Blood Loss, mL*
Field tourniquet	2.8 ± 0.9	1.9 ± 0.8	387 ± 66.6	995 ± 479.6
Conversion (pneumatic tourniquet)	3.1 ± 0.9	1.7 ± 1.1	247 ± 117.6	467 ± 264.8

*Mean ± standard deviation.

In conversion trials, status results showed that all 30 pneumatic tourniquet uses were effective to stabilize the patient. Fifteen pneumatic tourniquets were placed at the correct site; 15 were placed incorrectly. Pressures applied by pneumatic tourniquets were sufficient in 21 uses and insufficient in 9 uses. Overall, 15 trials were satisfactory and 15 were unsatisfactory (incorrect placement in 15, of which 9 were loose). The mean pressure and blood loss were 247 ± 117.6mmHg and 467 ± 264.8mL, respectively. The mean conversion trial time was 3.1 ± 0.9 minute. Ease of conversion varied between 3 and 5, with a median of 4. Conversion trials began with the field tourniquet in place at a pressure that had controlled hemorrhage, yet the transilluminated manikin wound served as feedback that signified uncontrolled hemorrhage.

Control Group: No Personal Protective Equipment (PPE0)

Field tourniquet trial status results showed that all 10 tourniquet uses without PPE stabilized the patient. There were nine satisfactory tourniquet results with correct placement and sufficient pressure. There was one unsatisfactory result, with incorrect placement as well as insufficient pressure. The median field tourniquet pressure was 372mmHg. The median blood loss was 403mL (Figure 1). Ease of use in field tourniquet trials in the PPE0 group was either 4 or 5, with a median of 5.

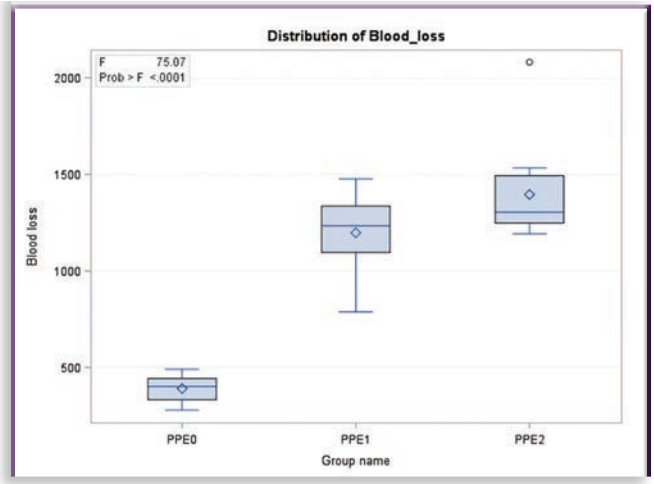
Without PPE, all 10 conversions to pneumatic tourniquet stabilized the patient. However, only 5 of these 10 conversions were satisfactory and placed at the correct site. Six of the 10 conversions had sufficient pressure, and 4 of the 10 conversions were applied too loosely. Median conversion pressure and blood loss were 266mmHg and 365mL, respectively. Ease of conversion was 4 in each conversion trial in PPE0.

PPE1: Personal Protective Equipment Group 1

The field tourniquet trial status results for PPE1 showed that all 10 tourniquet uses stabilized the patient and had sufficient pressures. Nine tourniquets were placed at the correct site, with satisfactory results. One tourniquet was placed incorrectly with unsatisfactory results. In PPE1, median tourniquet pressure and blood loss were 386mmHg and 1234mL, respectively. Ease of field tourniquet use in PPE1 was either 4 or 5, with a median of 4.

In conversion to pneumatic tourniquet use, patient status results showed that all PPE1 conversions stabilized the patient. Four conversions were satisfactory. There was incorrect placement in six conversions, three of which were also

FIGURE 1 *Results of field tourniquet trials for blood loss by group.*



The vertical boxplot graphically depicts blood loss results of 30 field tourniquet trials among three groups of personal protective equipment (PPE). The control group with no PPE (PPE0) resulted in less mean blood loss than both PPE1 and PPE2 by differences of 805mL and 1004mL, respectively ($P < .05$, both). The PPE2 – PPE1 mean difference of 199mL was not statistically significant ($P > .05$). The box top is the third quartile (Q3 or 75th percentile), the box bottom is the Q1 (25th percentile), the up whisker is the 95th, and the down whisker is the 5th. The central line is the median (Q2 or 50th percentile), and the diamond is the mean. The circle is a maximum.

applied too loosely. In PPE1, median pressure and blood loss were 267mmHg and 553mL, respectively. Ease of conversion ranged from 3 to 5, with a median of 4.

PPE2

The field tourniquet trial status results for PPE2 showed that all tourniquet uses stabilized the patient. In each case, the tourniquet was placed at the correct site with sufficient pressure, with satisfactory results. Median tourniquet pressure and blood loss were 421mmHg and 1305mL, respectively. Ease of use in tourniquet trials was either 4 or 5, with a median of 4.

For PPE2, conversion status results showed that all conversions to pneumatic tourniquet use stabilized the patient. However, in 4 of 10 cases, the tourniquet was placed incorrectly, and the results were unsatisfactory. Among these four instances, two tourniquets were applied too loosely. Median pneumatic tourniquet pressure and blood loss were 291mmHg and 289mL, respectively. Ease of conversion ranged from 3 to 5, with a median of 4.

Intergroup Comparisons: PPE1 – PPE0, PPE2 – PPE0, and PPE2 – PPE1

Comparing the control group, PPE0, to PPE1, the differences (PPE1 – PPE0) in mean blood loss for a field tourniquet trial, a conversion trial, and a test were 805mL, 233mL, and 1038mL, respectively. All were more for PPE1.

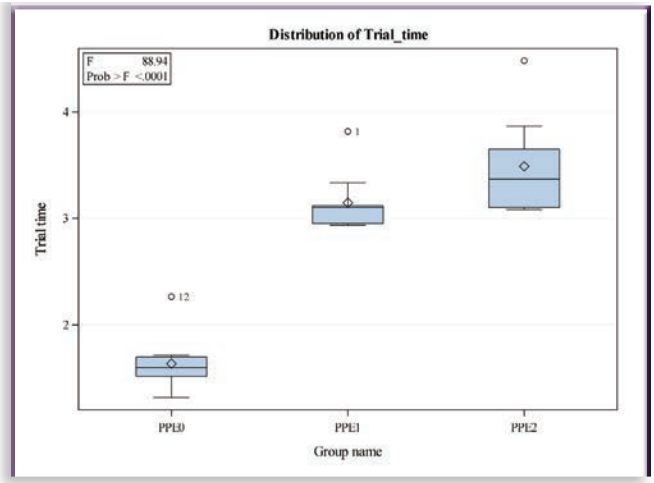
Comparing PPE0 to PPE2 (PPE2 – PPE0), the differences in mean blood loss for a field tourniquet trial, a conversion trial, and a test were 1004mL, –84mL, and 920mL, respectively.

Comparing PPE1 to PPE2 (PPE2 – PPE1), the differences in mean blood loss for a field tourniquet trial, a conversion trial, and a test were 199mL, –318mL, and –118mL, respectively.

Donning Delays

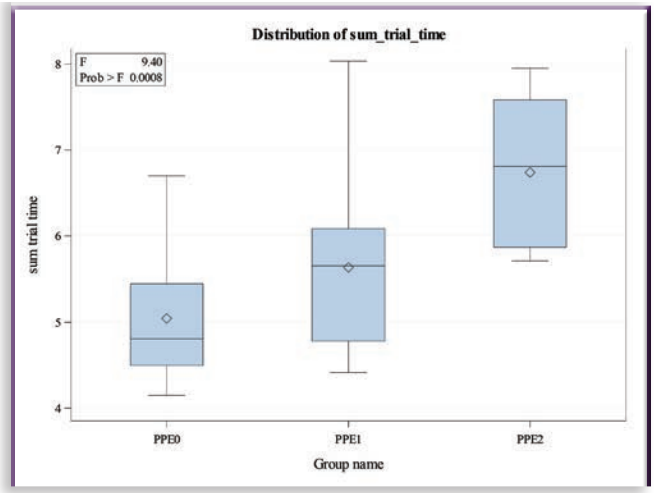
The pattern of results among groups for field tourniquet trial time (Figure 2) did not match the corresponding pattern of blood loss seen in Figure 1. Also, the results pattern for test time (i.e., sum trial time, of a field tourniquet trial and its conversion trial time, Figure 3) did not align with either field tourniquet trial blood loss or field tourniquet trial time in Figures 1 and 2, respectively. The field tourniquet trial blood loss correlated moderately with test time (Figure 4).

FIGURE 2 *Trial time results of field tourniquet use by group.*



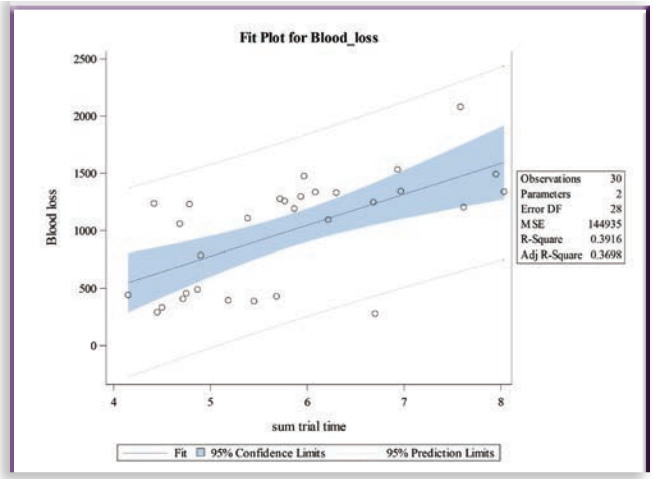
The boxplot depicts field tourniquet trial time results among PPE groups. The pattern of time results nearly matched that of blood loss in Figure 1. PPE0 took less trial time than both PPE1 and PPE2 by differences of 1.5 and 1.9 minutes, respectively ($P = .0002$, both). The PPE2 – PPE1 mean difference of 0.34min was not statistically significant ($P = .053$). The maximums are circles, and the labels are the test number.

FIGURE 3 *Sum trial time results in sum of a field tourniquet trial and its conversion trial by group.*



The boxplot depicts the sum trial time results being a summing of paired trials (field tourniquet trial and its conversion trial) among PPE groups. The pattern here was significant (P = .0008 by ANOVA), but it did not match the pattern of blood loss or of trial time in Figures 1 and 2. The PPE0 – PPE2 mean difference of 1.69 minutes was significant ($P = .0001$; 95% CI, –2.70 to –0.68 minute). Likewise, PPE1 – PPE2 difference of 1.10 minutes was significant ($P = .02$; 95% CI, –2.11 to –0.09 minute). The PP0 – PPE1 mean difference of –0.60 minute was not significant ($P = .17$; 95% CI, –1.61 to –0.42 minute).

FIGURE 4 *Correlation results between blood loss and test time (sum of paired trial times).*



The chart depicts a linear regression correlating field tourniquet trial blood loss to sum trial time, a sum of field tourniquet trial time and conversion trial time. The 30 data points are circles. The regression line is dark blue. The fit of the line has its 95% confidence limits in the shaded area and its 95% prediction limits bounded by the dashed line. The adjusted R^2 value, 0.3698, was used as a modified version of R^2 to adjust for predictors that are not significant in a regression model. Compared with a statistical model with additional input variables, the lower adjusted R^2 indicated that the additional input variables did not add value to the model. The proportion, 36.98%, of the variance in tourniquet trial blood loss was predictable from its sum trial time.

Donning delays, which were accounted in the field tourniquet use during the time to stop bleeding, were at an uncontrolled hemorrhage rate of 500mL/min. PPE0 had no delay: its mean blood loss was 392mL (Table 3). Compared with PPE0, PPE1 had a calculated mean donning delay of 1.4 minutes (rounded) of bleeding, which cost an extra 712mL of blood loss (500mL/min × 1.4 minutes), a 1.8-fold increase (712mL/392mL). Compared with PPE0, PPE2 had a delay of 1.7 minutes (rounded) costing 863mL more blood loss (500mL/min × 1.7 minutes), a 2.2-fold increase (863mL/392mL). In the two comparisons (PPE1 – PPE0 and PPE2 – PPE0), the extra loss divided by the mean blood loss in their field tourniquet trial yielded their donning delay effect sizes as 88% (712mL/805mL) and 86% (863mL/1004mL), respectively. The study donning effect size averaged 87%.

Compared to control, donning PPE delayed control of bleeding by long times (1.4 minutes and 1.7 minutes), but the difference between the two PPE groups was short, 0.3 minute (Table 3). Results of wearing PPE did not slow field tourniquet application or its conversion (Table 4). Altogether, the vast majority of blood loss was from how long it took to don PPE.

Discussion

The main finding of this simulation study was that how long it took to don PPE delayed when bleeding was stopped. The delays for the two PPE groups were 1.4 minutes and 1.7 minutes. Compared to the control group blood loss, 392mL, PPE delay caused excess losses that averaged 2.3-fold more, 904mL (805mL and 1004mL). However, wearing PPE did not slow field tourniquet application or its conversion.

Risk of hemorrhagic shock is associated with both the blood loss volume and its rate of loss. Both were substantial. Delays postponed bleeding control and worsened losses to increase risk of shock. If shock onset occurs before bleeding control, then such delay would contribute to shock duration and shock volume[12] (shock duration × shock severity). The present finding of delay effect sizes, averaging 87% of blood loss in the period of uncontrolled bleeding before tourniquet use, aligns well with previous sizes, which were found to be 80%[8] and 86%.[10] To date when sought, the size has been narrowly consistent in its recurrence and in its magnitudes. The key to patient outcome was time to stop bleeding, which was delayed by donning PPE. However, donning PPE had tradeoffs, including mitigated risks to the wearer and patient from injury, illness, or spread of infection. This finding indicates speed-safety tradeoffs among caregivers and patients (Table 5). Caregiving speed, treatment effectiveness, and safeguards are important to readiness: a warning to don PPE is key. As simulated, failure to communicate is risky and bloody.

TABLE 3 *Results of Time to Stop Bleeding and Blood Loss by Group*

	Time to Stop Bleeding, min		Blood Loss, mL	
Group	Field Tourniquet*	Conversion (Pneumatic Tourniquet)*	Field Tourniquet*	Conversion (Pneumatic Tourniquet)*
PPE0 (control)	0.9 ± 0.25	1.7 ± 0.98	392 ± 70.2	417 ± 206.3
PPE1	2.3 ± 0.21	1.8 ± 1.06	1197 ± 192.8	650 ± 299.4
PPE2	2.6 ± 0.40	1.6 ± 1.29	1396 ± 266.2	333 ± 183.7

*Mean ± standard deviation.
PPE = personal protective equipment.

TABLE 4 *Results of Other Times by Group for Tourniquet Application, Conversion, and Test*

	Tourniquet Application (Field Tourniquet)*		Conversion (Pneumatic Tourniquet)*	
Group	Trial Time	Posttime	Trial Time	Posttime
PPE0 (control)	1.6 ± 0.25	0.8 ± 0.06	3.4 ± 0.70	1.7 ± 0.90
PPE1	3.1 ± 0.26	0.8 ± 0.14	2.5 ± 1.03	0.7 ± 0.18
PPE2	3.5 ± 0.44	0.9 ± 0.13	3.3 ± 0.73	1.7 ± 0.84

*Mean ± standard deviation.
PPE = personal protective equipment.

TABLE 5 *Algorithmic implications of tradeoff among results in tourniquet interventions*

Personal Protective Equipment Use		
	No	**Yes**
Donning	• Less time to stop bleeding • Less blood loss	• More time to stop bleeding • More blood loss
Wearing	• Higher risk of injury or disease spread • Other than to stop bleeding, times and blood losses are affected little	• Lower risk of injury or disease spread • Other than to stop bleeding, times and blood losses are affected little

The minor finding of this study is that the conversion process was inadequately realistic because the manikin was not designed to simulate conversion. The stepwise conversion procedure was workable, as a caregiver could learn its steps in order, but the hard manikin provided too firm a hand-feel. In addition, it did not allow the pneumatic tourniquet to deform and realistically indent the limb surface, which distributes compressive forces into the deeper, underlying tissues. Under a 6mm layer of silicone-like skin, the manikin has thin piezoelectric transducers undergirded by a layer of hard plastic. Such hardness may protect transducers from high bending forces and allow reliable readings with flat tourniquets. However, pneumatic bladders are rounded. The EMT inflatable bladder has two stacked layers—one toward the limb and one away from the limb. The nylon layers are heat-sealed together at their edges to form a long, wide band, which also has sealing extensions that incompletely cross for air to flow lengthwise. Sealing extensions are evenly spaced lengthwise along the band. The sealing stabilizes the band on the limb as layers are bonded together only at sealed areas, which dimple the bladder on inflation to limit rounding. Otherwise, a bladder without sealing extensions or dimpling takes the form of an inner tube, which rolls down a conically shaped limb to migrate distally as pressures lessen because the limb is narrower. In use, one can see the EMT band is initially uninflated and flat on the limb. With each pump of the hand bulb to inflate the bladder, the EMT incrementally rounds up on its topside away from the skin. The bottom-side rounds similarly, but radially inward toward the skin. The pumping-rounding increments separate the bladder's topside and bottom-side layers, except where they are sealed.

On a nearly incompressible manikin, such layer separation leaves the sealed areas suspended between the topside and bottom-side to leave gaps between the sealed areas and the skin. The adjacent areas to the sealed areas round to lift the sealed areas from the skin and offload transducers. In real patients, the computerized tomography of limbs with applied EMTs showed no gapping from the skin[13] because the human limb is more compressible than the manikin. However, the manikin is nearly incompressible, so its transducers detect lower pressures at gaps where the sealed areas have less contact. Thus, when sampled over multiple transducers, there are some low pressures resulting from this design artifact in the manikin. Because of the hardness, an algorithm such as averaging nearby pressures would under-sample clinically relevant pressures. Because the manikin is unrealistically stiff, such undercounting underappreciates EMT capability. The manikin was previously shown to be suboptimal as a platform or a tool to simulate conversion of a field tourniquet to a pressure dressing.[14] Likewise here, the manikin was suboptimal in simulating conversion of a field tourniquet to a pneumatic tourniquet. Even if in the future the field tourniquet is converted to another field tourniquet on the manikin, it will still have the problem of flashing lights when bleeding is controlled to start each conversion trial. We likely could not see these problems in the prior study because gauze covered the wound and its lights.[14] Perhaps a software input overrides the mechanical input, since the manikin's purpose is to train a user to control hemorrhage, not to convert types of control. Should such an optimal manikin be developed, researchers and makers should provide input into its requirements in order to eventually fulfill the needs of the operational health community.

Limitations of this study are numerous because its design dealt with one caregiver and narrowly simulated health care. Simulation of multiple people might offer team or group data that are more representative of caregivers. The PPE that were selected were readily available, but also similarly not diverse. The manikin is passable as a limb segment to practice the conversion step order, but as a task trainer, the manikin poorly suits conversion because it is nearly incompressible and provides incorrect feedback.

Conclusions

This study developed a method of simulating PPE donning effects on tourniquet use. How long it took to don equipment delayed the time to stop bleeding and increased blood loss, but wearing PPE slowed down neither field tourniquet application nor its conversion.

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Author Contributions

JFK participated in study conception and design. JFK and MAD resourced, managed, and oversaw the study. While JFK collected data, both JFK and TDL analyzed data. All authors participated in writing the manuscript and approved its final version.

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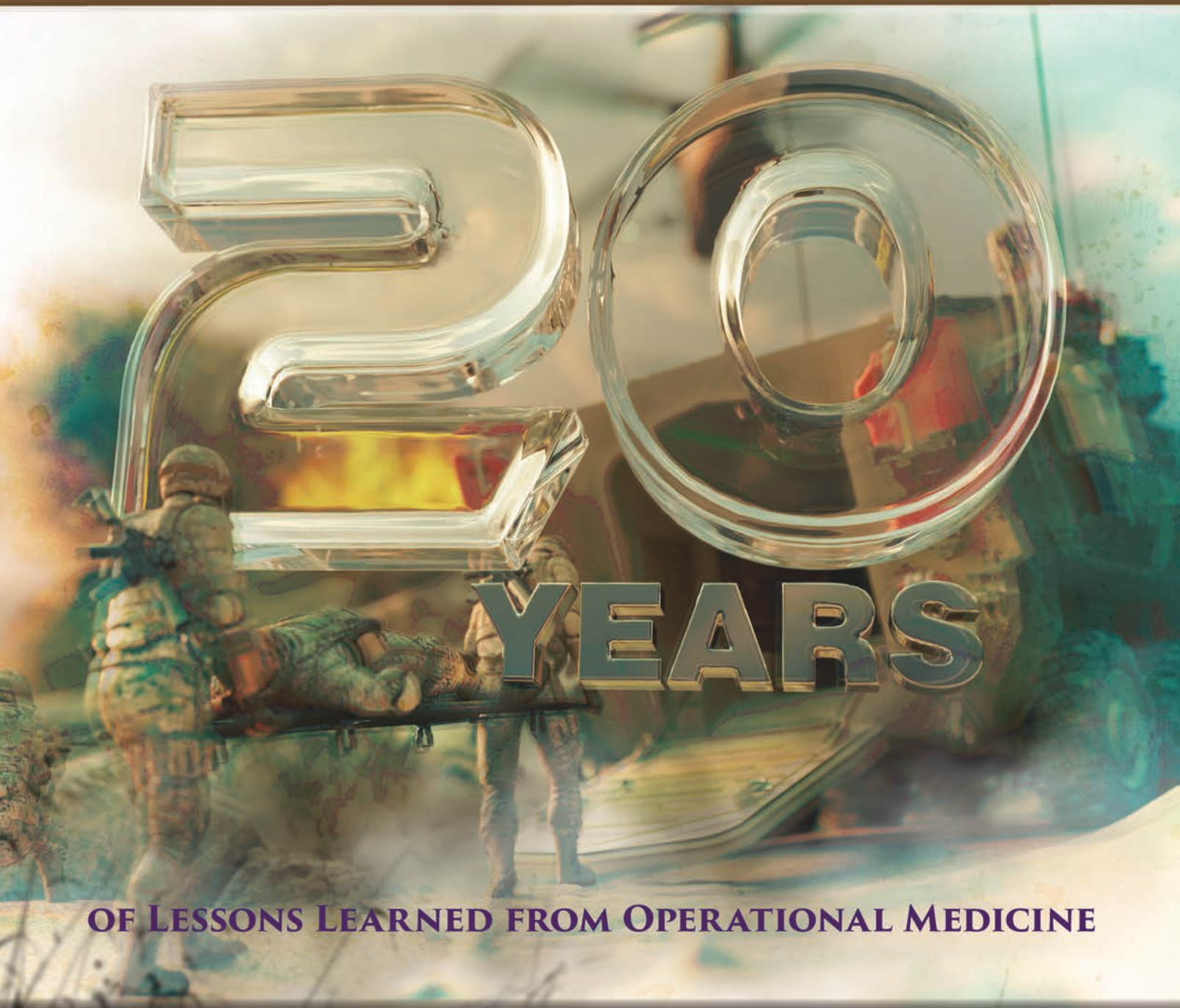

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