Preventing Hypothermia: Comparison of Current Devices Used by the US Army in an In Vitro Warmed Fluid Model

Paul B. Allen, DSc, PA-C, Steven W. Salyer, PA-C, Michael A. Dubick, PhD, John B. Holcomb, MD, and Lorne H. Blackbourne, MD

Background: The purpose of this study was to develop an in vitro torso model constructed with fluid bags and to determine whether this model could be used to differentiate between the heat prevention performance of devices with active chemical or radiant forced-air heating systems compared with passive heat loss prevention devices.

Methods: We tested three active (Hypothermia Prevention Management Kit [HPMK], Ready-Heat, and Bair Hugger) and five passive (wool, space blankets, Blizzard blankets, human remains pouch, and Hot Pocket) hypothermia prevention products. Active warming devices included products with chemically or electrically heated systems. Both groups were tested on a fluid model warmed to 37°C versus a control with no warming device. Core temperatures were recorded every 5 minutes for 120 minutes in total.

Results: Products that prevent heat loss with an actively heated element performed better than most passive prevention methods. The original HPMK achieved and maintained significantly higher temperatures than all other methods and the controls at 120 minutes ($p < 0.05$). None of the devices with an actively heated element achieved the sustained 44°C that could damage human tissue if left in place for 6 hours. The best passive methods of heat loss prevention were the Hot Pocket and Blizzard blanket, which performed the same as two of the three active heating methods tested at 120 minutes.

Conclusions: Our in vitro fluid bag "torso" model seemed sensitive to detect heat loss in the evaluation of several active or passive warming devices. All active and most passive devices were better than wool blankets. Under conditions near room temperature, passive warming methods (Blizzard blanket or the Hot Pocket) were as effective as active warming devices other than the original HPMK. Further studies are necessary to determine how these data can translate to field conditions in preventing heat loss in combat casualties.

Key Words: Passive heating, Active heating, Blankets, In vitro model.

(*J Trauma.* 2010;69: S154–S161)

Submitted for publication February 26, 2010.
Accepted for publication April 22, 2010.

From the US Army Institute of Surgical Research, Fort Sam Houston, Texas.
The views and opinions expressed in this article are those of the authors and do not reflect the official policy or position of the United States Air Force, United States Army, United States Navy, Department of Defense, or the US government.
None of the authors has any affiliation with the manufacturer of these products, and the authors have no potential conflicts of interest to declare.
Address for reprints: Michael Dubick, PhD, US Army Institute of Surgical Research, 3400 Rawley E Chambers Avenue, San Antonio, TX 78234; email: Michael.dubick@amedd.army.mil.

DOI: 10.1097/TA.0b013e3181e45ba5

Hypothermia, defined as a core temperature of <35°C[1–3] secondary to hemorrhagic shock or trauma,[4,5] is as difficult for medical providers to treat today as it was in World War I.[6] It is often an overlooked and sometimes fatal complication of trauma.

Although the prehospital civilian or casualty care curriculum stresses the importance of preventing heat loss and keeping multisystem trauma patients warm, sometimes this critical step is overlooked during care of trauma patients. One study observed that 43% of trauma patients arriving at a hospital were hypothermic.[7]

There are many implications of hypothermia in multisystem trauma patients. Because every body system is affected by hypothermia, there are strong relationships among sepsis, coagulopathy, acidosis, and multiorgan failure in these critically injured patients.[7] Hypothermia's relationship to coagulopathy and shock has been well documented.[1,2,4–17] This "triad" is a significant contributing factor to the mortality of trauma patients and has been noted as a major reason for resistance to resuscitation after trauma.[6,11,13,14,16] This acquired coagulopathy, particularly in trauma patients who require massive transfusion, accounts for a large percentage of early trauma deaths among both civilians and military personnel.[2,3,8]

The triad of hypothermia, coagulopathy, and acidosis may be more difficult to reverse in a desert environment.[6,18] This coagulopathy of trauma affects at least one in four seriously injured trauma patients; and etiologies include direct effects of hemorrhage, hemodilution, hypothermia, and acidosis.[11] Some data suggest a possible correlation with survival. For example, one study in particular showed that in normothermic patients, the survival rate was 97.5%; whereas in hypothermic patients, it was 75%.[19] Another conclusion from the same study observed that 87.5% of patients who were hypothermic on arrival needed surgery versus 64.5% of normothermic patients. Eastridge et al.[12] showed a correlation between hypothermia and the need for massive transfusion in multiple trauma victims and asserted that blood transfusion requirements are directly proportional to core temperature. Even mild hypothermia (34–36°C) has multiple untoward physiologic effects; and studies demonstrated an increased incidence of postoperative wound infections, coagulopathy, myocardial ischemia, and a decrease in peripheral circulation (which may increase tissue hypoxia, thus making wounds more susceptible to infection).[1,2,20] Arthurs et al.[21] looked retrospectively at 1-year's worth of trauma patients present-

ing to their combat support hospital in Iraq and found 100% mortality in patients presenting with temperatures of 33°C or less and a Glasgow Coma Scale score <8. These data suggest that a critical temperature range for the multisystem trauma patient is 34°C to 36°C.[21]

Combating hypothermia in the prehospital setting (US Army echelons I and II for the military) has plagued medical providers since the discovery of this metabolic derangement.[22] Hypothermia by itself presents treatment challenges. Combined with a shock state and hypovolemia, it can be a disastrous event that will worsen and quickly lead to decompensation in critically injured patients.

Since the US Army developed the Tactical Combat Casualty Care (TCCC) model, casualty evacuation care has presented a challenge for providers to prevent hypothermia in trauma patients.[21,22] TCCC advances have driven medical device markets to make products whose performances have not been validated by independent studies. Thus, medical providers in the field are forced to base their procurement decisions on either personal anecdotal experience or manufacturer claims of performance or simply to rely on old methods of passive prevention of heat loss.

We developed a torso model constructed from nine 5,000-mL bags of warmed PrismaSATE (Gambro, Lakewood, CO) dialysate solution and used this model to evaluate the performance of various hypothermia prevention methods currently available in the US Army medical supply system for TCCC. We had three main research questions: (1) Are devices with active chemical or radiant forced air heating systems better than passive prevention of heat loss? (2) Are passive warming systems as good or better at preventing heat loss when compared with actively heated devices? (3) Do any of the devices with an actively heated component achieve temperatures known to cause burns on human skin? This study attempted to quantify the efficacy between the main hypothermia prevention kits available at the point of injury and military echelon I and II facilities and to establish a rank order of greatest to least in terms of loss of temperature, gain of temperature, or no change in our fluid model. The results of this study should also apply to treating hypothermia in the civilian community.

MATERIALS AND METHODS

This study was a prospective laboratory trial designed to evaluate current products used to prevent hypothermia. Our "torso" model used nine 5,000-mL bags of PrismaSATE (Gambro, Lakewood, CO) dialysate solution for continuous renal replacement therapy. This fluid was composed of 3.05 g magnesium hydrochloride, 5.4 g lactic acid, 7.08 g sodium chloride, 2.21 g sodium bicarbonate, and 0.314 g potassium chloride in a total volume of 5,000 mL. These bags were configured to the size and weight of an adult human torso (~60% of 70 kg or 48.6 kg) and heated to 38.5°C.

In preliminary studies, fluid bags were heated to 37°C and allowed to cool at ambient temperature to provide baseline negative control values without hypothermia prevention. The average time for this model to cool from 37°C to 34°C was 2 hours; hence, this became the testing time in this study. Models had one indwelling thermistor probe in a representative "core" bag, and surface temperature probes were attached dorsally and ventrally to track changes in temperature every 5 minutes for 2 hours.

We tested two broad groups of hypothermia prevention: active and passive. In the active group, we evaluated two Hypothermia Prevention Management Kits (HPMKs) (North American Rescue Products, Greer, SC)—the original and a newer version introduced during the course of this study. We also evaluated the Ready-Heat (RH) blanket (TechTrade LLC, New York, NY) and the Bair Hugger Model 505 (Arizant, Eden Prairie, MN) forced air warmer. The HPMK consists of the RH blanket and either the Blizzard blanket or Heat Reflective Shell (HRS) described below. The Blizzard and the HRS are components of the original and the new HPMK, respectively. The RH blanket is constructed of a strong weave paper with four pouches containing the exothermic chemical powder mixtures and is designed to fit on the torso of a casualty. The Bair Hugger is a forced air warming device consisting of a warming unit and telescoping hose that attaches to a reinforced paper blanket with cells that provide venting of the warmed air. The device requires electrical power, and the high setting of the device is listed as 40°C. These products are the standard active hypothermia prevention devices currently used by the US military and are listed in the Joint Theater Trauma System Clinical Practice Guidelines on Hypothermia Prevention, Monitoring, and Management (November 2008) for hypothermia prevention in trauma patients from the current war in Iraq. The North Atlantic Treaty Organization stock number for each item available in the US Army Inventory is listed in Table 1.

In the passive group, we compared the US Army standard issue wool blanket, space blanket, human remains pouch (HRP), Blizzard Blanket (Performance Systems Medical Division, Houston, TX), and HRS. Because both the Blizzard Blanket and HRS are available as single units without the RH, they were also evaluated alone. In addition, the HRP, wool blanket, and space blanket were evaluated as a passive system in combination, known as the Hot Pocket. The space blanket, also known as the combat casualty care blanket, has a reflective side. The blanket used in this study was a heavier plasticized tarpaulin version that has cross-hatched plastic thread reinforcements to confer strength. The Blizzard blanket is a large reflective wrap designed to cover most adults completely and is made from a proprietary material called Reflexcell. The HRP or body bag is the current device used in the military and is constructed of an outer plastic or canvas cover with a rubber leak proof inner core. The HRS is constructed from a polyolefin, 4-ply, composite fabric with a protected nonconductive thermal reflective layer that is waterproof and windproof.

Bags were placed in the center of a calibrated warming cabinet, model 5618 (Getinge, Rochester, NY), and set to a temperature of 37.8°C. This temperature setting actually achieved a core temperature closer to 38.5°C consistently. During preliminary test runs, we denoted exact times relevant to degradation of temperature on removal of the fluid bags from the warming cabinet to account for initial radiant and

TABLE 1. Mean Core Temperatures of the Model at Times After Wrapping in Hypothermia Prevention Products

Hypothermia Prevention Product Active (A) or Passive (P)		Mean Core Temperature, °C			
Name	**NSN***	**At 30 Minutes**	**At 60 Minutes**	**At 90 Minutes**	**At 120 Minutes**
Original HPMK (A)	6515-01-532-8056	36.76 ± 0.11†‡	36.76 ± 0.23†‡	36.74 ± 0.33†‡	36.7 ± 0.32†‡§
New HPMK (A)	6515-01-532-8056	36.6 ± 0.14‡	36.4 ± 0.14†‡	36.18 ± 0.18†‡	35.98 ± 0.23†‡
New RH (A)	6532-01-525-4062	36.72 ± 0.22†‡	36.5 ± 0.37†‡	36.28 ± 0.38†‡	36.08 ± 0.38†‡
RH (A)	6532-01-525-4062	36.56 ± 0.15‡	36.34 ± 0.17†‡	36.18 ± 0.24†‡	36.06 ± 0.29†‡
Bair Hugger (A)	6530-01-463-6823	36.54 ± 0.24‡	36.44 ± 0.25†‡	36.18 ± 0.37†‡	35.92 ± 0.37†‡
Blizzard blanket (P)	6532-01-524-6932	36.48 ± 0.18‡	36.1 ± 0.12†‡	35.86 ± 0.11†‡	35.6 ± 0.10†‡
HRS (P)	Pending	36.46 ± 0.11‡	36.02 ± 0.20†‡	35.58 ± 0.26†‡	35.16 ± 0.35†‡
Hot pocket (P)		36.66 ± 0.15‡	36.42 ± 0.13†‡	36.18 ± 0.16†‡	35.94 ± 0.15†‡
HRP (P)	9930-01-331-6244	36.14 ± 0.23	35.6 ± 0.26	35.08 ± 0.24	34.56 ± 0.09
Space blanket (P)	7210-00-935-6666 or 7210-01-463-5431	36.34 ± 0.15‡	35.96 ± 0.31‡	35.58 ± 0.30†‡	35.12 ± 0.18†‡
Wool blanket (P)	7210-00-282-7950 or 7210-00-935-6665	35.9 ± 0.1	35.26 ± 0.09	34.86 ± 0.17	34.44 ± 0.15
Control		36.26 ± 0.21	35.44 ± 0.27	34.66 ± 0.27	33.98 ± 0.17

* NSN is the NATO (North Atlantic Treaty Organization) stock number assigned to products.
† $p < 0.05$ from control.
‡ $p < 0.05$ from wool blanket.
§ $p < 0.05$ from all other products.
Data represent the means ± SD of five separate determinations at each time point.

convective heat losses before torso model setup. No test began until indwelling temperatures were at exactly 37°C. Internal room temperature was maintained between 22.3°C and 22.7°C and verified with both digital- and mercury-type thermometers placed throughout the room. Temperatures were checked every 15 minutes and never varied outside this range.

Two groups of nine bags were heated simultaneously in the warming cabinet and randomly selected for each test to decrease variability. Only two tests were done per day on bags warmed continuously in the cabinet for 12 hours. The groups of bags were placed on a stainless steel operating table. The bags were then stacked in the configuration of a torso. Temperature measurements of the dorsal surface, ventral surface, and core were obtained every 5 minutes during test runs with the Omega HH 84 thermo collector (Omega Engineering, Stamford, CT). The manufacturer's specifications list variance as 0.1°C for accuracy. The devices self-calibrate on powering up and running self-diagnostic tests. If the probes are not functioning, the temperature will not be displayed, and a message reading "over" will be visible. Probes were replaced if temperature monitoring malfunctioned. Two Omega (Omega Engineering) hypodermic probes (model number HYP1-30-1/2T-G-60-SMP-WM) were used for each test for core measurements, and two additional probes (model number HYP2-21-1-1/2-T-G-48-OSTW-M) were used to monitor surface temperatures.

A mercury thermometer was then compared to ensure that all devices were within reasonable variance as listed by Omega. No variation was detected between probe readings, and minimal variation was detected between the digital and the mercury thermometers (0.1–0.2°C).

The core probe was placed on a 6-inch rod and inserted by using a Luer adapter to ensure that the probe was in the center of the representative core bag. Surface probes were placed directly underneath actively heated elements and not on air bubbles once the model was placed on the table.

Alternating ends of the table were used between runs to account for conduction of heat to the table, and table temperature was checked to ensure equilibrium with the room environment before each test. The table was turned during each consecutive trial so that the head of the model was farthest away from the air flow from the air conditioning unit to control for convective forces.

For combined core temperature results, data were analyzed using repeated measures with two-way analysis of variance with time and device as the variables. Tukey-Kramer adjustment was used for multiple comparisons at each time point. To determine whether there was a significant drop in temperature at the end of the experiment when compared with the baseline for each individual device, a one-way analysis of variance with repeated measures was used.

Core temperatures were compared among all devices relative to the untreated controls and the Army standard issue wool blanket. Also, at 120 minutes, we compared whether any of the passive devices maintained temperature in addition to the active warming devices. Surface temperatures were also evaluated to determine whether devices with an actively heated component reached temperatures known to cause damage to human skin. Each device was tested five separate times.

Data are presented as mean ± SD. A p value of <0.05 was considered statistically significant. The times listed in Table 1 were selected for statistical comparison to provide medical personnel treating casualties in the field, reference time points. For example, an evacuation time of 30 minutes might apply to some situations whereas 120 minutes may be more realistic in others.

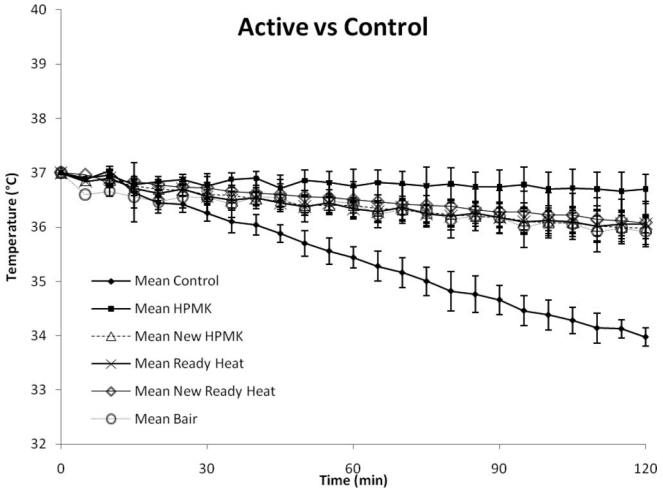

Figure 1. Temperature maintenance of active heating products (HPMKs, Bair Hugger, and RHs) during the 2-hour period compared with untreated controls. The original HPMK maintained the highest temperatures compared with the others at 120 minutes ($p > 0.05$). All products maintained significantly higher temperatures than controls and wool blankets from 60 minutes to 120 minutes. The HPMK was significantly better than the controls and wool blankets from 20 minutes to 120 minutes. Both RHs were better than the controls and wool blankets from 35 minutes to 120 minutes. Data represent the mean + SD of five separate determinations for each product.

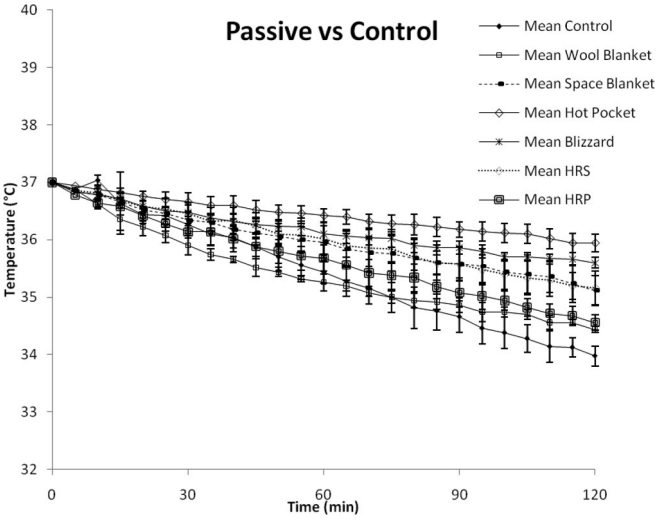

Figure 2. Temperature maintenance of passive warming products (wool blanket, space blanket, HRP, Hot Pocket, HRS, and Blizzard) during the 2-hour period compared to untreated controls. The Hot Pocket maintained statistically higher (p, 0.05) temperatures compared with the wool blankets and controls from 15 minutes to 120 minutes. All other passive products were better than the controls and wool blankets from 30 minutes to 120 minutes. The wool blanket and HRP were not better than the untreated controls. Data represent the mean + SD of five determinations for each product.

RESULTS

Control Group

In the untreated control group, the average time for our model to cool from 37°C to 34°C at an ambient controlled room temperature of 22.3°C to 22.7°C was 2 hours (Figs. 1 and 2). In this group, the mean temperature was 36.2°C at 30 minutes, 35.44°C at 60 minutes, and 33.9°C at 120 minutes (Table 1).

Active Warming Devices

A comparison of the active hypothermia products versus the control group is shown in Figure 1. All active warming devices maintained core temperatures in the fluid model significantly better than controls or the wool blanket from 60 minutes or earlier (see below) to the end of the 120-minute experimental period (Fig. 1; Table 1).

Hypothermia Prevention Management Kit

Once the fluid model was constructed and a core temperature of 37°C was assured, the kit was wrapped in sequence; the RH heating blanket was placed over the dorsal surface and the reflective shell (Blizzard blanket) over the heating blanket and sealed according to its recommended use. Recording began at a core temperature of 37°C. Mean core temperature was 36.76°C at 30 minutes and 60 minutes and fell only to 36.70°C at 120 minutes (Fig. 1; Table 1). The HPMK maintained temperature better than controls or the wool blanket from 20 minutes through 120 minutes (Fig. 1). In addition, at 120 minutes, the HPMK maintained a significantly higher core temperature than all other devices evaluated. Also, the mean highest surface temperature, taken as a direct reflection of RH performance, was 41.68°C at 90 minutes.

During the course of this study, a new version of the HPMK was introduced; hence, we included that kit in our evaluation, as well as comparisons between the two RH blankets and the two outer shells (see below). Mean core temperature in the new HPMK at 30 minutes was 36.6°C, falling only to 35.98°C at 120 minutes (Fig. 1, Table 1). This newer HPMK was better than controls in maintaining temperature from 35 minutes to 120 minutes of the experimental period. The average core temperature maintained by the new HPMK was statistically less than the original HPMK, only at 120 minutes. However, differences in the actual temperature maintained between the two kits did not achieve our definition of a clinically significant 3°C drop in temperature.

Bair Hugger (Model 505) Patient Warming Device

The fluid model was placed on the table, allowed to cool to 37°C, and then covered with the full-body blanket component of the Bair Hugger. The device was set on high temperature for the duration of the test. Average mean core temperature at 30 minutes was 36.54°C and dropped to 35.92°C at 120 minutes (Fig. 1, Table 1). The mean highest dorsal temperature, taken as a direct reflection of forced heat efficiency, was 35.56°C at 5 minutes.

RH Heated Medical Disposable Blanket

The RH blanket was opened, and 30 minutes was chosen as the time within the manufacturer's instructions to allow the device to heat properly. The fluid model was covered as one would cover a patient in the supine position and a standard Soffe (Fayetteville, NC) tan US Army issue T-shirt placed on the model between the heating elements and the device as per the manufacturer's guidance and in accordance with what would be readily available to a provider placing this device on a combat casualty. Mean core temperature was 36.56°C at 30 minutes, 36.34°C at 60 minutes, and 36.06°C at 120 minutes (Fig. 1, Table 1). The RH maintained temperature better than the controls or the wool blanket from 35 minutes to the end of the experiment. The mean highest surface temperature, taken as a direct reflection of RH performance, was 40.24°C at 5 minutes.

On initial observation, the new RH seemed to perform differently than the original. The SD observed in the temperature measurements was less compared with that of the original device, suggesting more uniform warming. Thus, the new RH was better than the controls or the wool blanket as early as 20 minutes after the start of the experiment and remained so throughout the rest of the experimental period (Fig. 1). Mean core temperature observed was 36.72°C at 30 minutes, 36.5°C at 60 minutes, and 36.08°C at 120 minutes (Fig. 1, Table 1). There were no statistical or clinically significant differences between the two RH products.

Passive Group

A comparison of the passive devices evaluated to the control group is illustrated in Figure 2. All devices other than the wool blanket and the HRP maintained core temperature better than controls from 60 minutes or earlier (see below) to the end of the experiment (Table 1).

Wool Blanket

For its ubiquitous presence, this product was also the poorest performer, with a temperature drop similar to that of the control group (Fig. 2). Mean core temperature was 35.9°C at 30 minutes and fell to 34.44°C at 120 minutes (Table 1).

Blizzard Blanket

This product performed well by itself, even matching the performance of the Bair Hugger and the RH during the first hour. Mean core temperature was 36.48°C at 30 minutes, 36.10°C at 60 minutes, and 35.6°C at 120 minutes (Fig. 2, Table 1). The Blizzard blanket maintained temperature better than the wool blanket as early as 15 minutes after the start of the experiment and maintained statistically higher temperatures for the remaining time (Fig. 2). In addition, at the end of the study, the core temperature maintained by the Blizzard blanket was not significantly different from that maintained by the active warming devices, new or original RH or the new HPMK.

Blanket, Combat Casualty, Type II (Space Blanket)

This blanket was placed over the fluid model and tucked in both sides for each test. Mean core temperature was 36.34°C at 30 minutes, falling to 35.12°C at 120 minutes (Fig. 2, Table 1). The space blanket also outperformed the wool blanket from 30 minutes until the end of the experiment (Fig. 2).

Human Remains Pouch

The HRP was wrapped over the fluid model in the manner it has been used to prevent hypothermia. The mean core temperature was 36.14°C at 30 minutes and fell to 34.56°C at 120 minutes (Fig. 2, Table 1). The HRP did not maintain core temperatures significantly better than the controls or the wool blanket in this study.

Hot Pocket (Combination of Two Wool Blankets, One-Space Blanket, and Inside HRP)

Our model was placed in the above listed configuration with wool blankets closest to the fluid bags, then space blanket, and then the HRP. The mean core temperature was 36.66°C at 30 minutes, 36.42°C at 60 minutes, and 35.94°C at 120 minutes (Fig. 2, Table 1). The Hot Pocket was very effective and maintained core temperatures better than the controls, the wool blanket, or HRP as early as 15 minutes after the start of the experiment and maintained this advantage for the remaining time (Fig. 2, Table 1). Also, at the end of the experiment, the Hot Pocket maintained core temperature of the fluid model in addition to all active warming devices except for the original HPMK.

Heat Reflective Shell

This blanket was the passive warming component in the newer version of the HPMK that we evaluated. Mean core temperature was 36.46°C at 30 minutes, 36.02°C at 60 minutes, and 35.16°C at 120 minutes (Fig. 2, Table 1). The HRS maintained temperature better than the wool blanket from 15 minutes to 120 minutes of the experimental period (Fig. 2). As we compared the original to the new HPMK, we also evaluated any differences between its passive components. There were no statistically significant differences in core temperature maintained between the Blizzard and the HRS at any time point.

Surface Temperature Evaluation

Surface temperatures were evaluated in products with an actively heated element (HPMK, RH, and Bair Hugger 505). Our interest was specifically in temperatures known to be dangerous to human skin through prolonged exposure. Maximum mean surface temperature achieved for the original HPMK system was 41.68°C at 90 minutes. Maximum mean surface temperature achieved for the original RH blanket alone was 40.24°C at 5 minutes. Maximum mean surface temperature achieved for the Bair Hugger 505 was 35.56°C at 5 minutes.

DISCUSSION

In this study, all products tested prevented the full 3°C drop that we predetermined to be clinically significant based on the literature. Then, the question of product efficacy hinges on individual casualty circumstances. If a patient is injured in a wilderness setting, such as an engagement in the

mountains of Afghanistan during the winter months, and if a first responder cannot make it to the casualty in a timely manner, then the patient is susceptible to developing hypothermia during the course of the combat action. If this patient's starting temperature at the beginning of resuscitation is at 33.5°C, then only 0.5°C becomes vitally important, because these data portend for poor outcomes below 33°C. So in this case, a device that allows for little heat loss would be critical, and use of a device such as the wool blanket, which was the poorest performer, would be inadequate.

The original HPMK maintained the highest temperatures when compared with all other methods ($p < 0.05$) with the narrowest margin of heat loss, whereas the new HPMK did not achieve the same temperatures when compared with the original HPMK that we evaluated. However, the rate of temperature loss was not significantly different between the two systems. In addition, comparisons between the RH blankets in the original and new HPMK systems as well as comparisons between the Blizzard and the HRS blankets indicated that they performed similarly to each other in maintaining temperature during the 2-hour experimental period. Since the completion of our study, a new water-resistant shell was introduced into the HPMK. This shell may offer better performance than the HRS that we evaluated when used with the RH blanket as part of the HPMK. Preliminary data indicate that the RH blanket will not generate heat well if it becomes wet before activating (data not shown). Thus, a new water-resistant shell should improve the overall performance of the HPMK, but it should be noted that this new shell or the newest system was not evaluated in this study.

For up to 1 hour, the rate of temperature loss between the original and the new outer blanket appeared identical. After 1 hour, there was some divergence suggesting that the Blizzard blanket may perform slightly better, but results were not statistically significant. One problem commonly noted with the Blizzard is that once the casualty or trauma patient is wrapped in it, you must open the blanket completely to reexamine the patient, reinforce dressings, or provide treatments. In addition, there are no access points to run intravenous lines or tubes outside of the device. It took an average of 3 minutes to open the Blizzard blanket completely and to set it up for the patient model under our experimental conditions. Despite its drawbacks, it was one of the top-performing products in our testing. The reflective skull cap provided with the HPMK system was not evaluated as a part of testing in our fluid model but is designed to prevent heat loss in the trauma patient from this area.

There were no significant differences in the rate of loss of core temperature between the RH blankets in the original and the new HPMK evaluated. Preparation time for the heating element to begin its chemical reaction is required with the RH. This time needs to be considered when using these devices on patients in the field. The RH uses a metalloid exothermic reaction as the source of heat generation; and as a result, if particles are not agitated before placement and/or as particles become static, the heat generation properties are affected. Thus, in training first responders, recommending that they agitate the blanket periodically during the prewarming period to maximize mixing of the components for even heat generation would be beneficial. The individual unit's standard operating procedures and immediate action drills should include this time for preparing and agitating the heating element for this system at the first notification or realization of significant trauma-related casualties who will need to be evacuated for further care. For testing purposes, 30 minutes was chosen as the time for maximal heat generation in this study.

Regarding surface temperature among all the devices evaluated, none of them achieved the threshold temperatures considered to cause thermal injury.[23] These authors observed that the lowest surface temperature responsible for cutaneous burning was 44°C, and the time required to cause irreversible damage to epidermal cells at this temperature was ~6 hours. Several anecdotal reports of thermal burns from the original HPMK have circulated among military first responders. It is possible that compression of these devices might increase heat transfer, and some anecdotal reports related to thermal injury with the original HPMK refer to objects directly on the heating element that may have increased pressure over the patient's skin. Further study to determine whether environmental or patient factors are responsible seems warranted.

Limitations

Because this fluid model did not consist of a biological organism and had no basal metabolic activity, extrapolation of this study to efficacy in humans may be limited. This study looked at a very narrow focus of parameters with reference to surface heat and reduced rate of heat loss as measures of performance, as well as any data that could indicate harm to humans (e.g., absolute surface temperatures that would cause injury to tissue). Despite these limitations, the model was effective in detecting drops in temperature among the different devices. Therefore, we think our model would be useful to screen potential new products or combinations claimed to prevent hypothermia. Another limitation of this study is that we only studied these products at one environmental temperature. Thus, it is also unknown whether cooler ambient room temperatures would have produced different results. In the passive group, almost any single coverage device can be used by soldiers or first responders in the field, but we purposely limited our evaluation to devices available within the medical supply system that are purpose built for casualties.

CONCLUSIONS

From this testing, we cannot definitively conclude that all active methods are better than passive methods nor can we rank their performance as originally intended. Given the poor performance of the wool blanket when used alone during the course of this study, one must wonder about its utility given the advanced technologies available today. Traditional single coverage passive products like the wool blanket and the space blanket may be adequate for 30 minutes; but if evacuation times exceed 30 minutes, the HPMK, RH, or Bair Hugger 505 may be a better choice. The observations that chemically heated devices performed as well or better than the Bair Hugger that requires electrical power, and that some passive prevention products (Blizzard, Hot Pocket) performed as well

as the Bair Hugger system and the RH, is useful information for first responders who may need to keep casualties warm in the field or during evacuation; situations where power is unavailable. Also, we did not detect surface temperatures produced by the active warming devices that would indicate they would burn human skin.

The original HPMK maintained the highest temperatures to the starting 37°C compared with the other methods tested in preventing heat loss from this fluid model. This exact product is no longer available. However, the newer HPMK performed similarly to the original, and the slight difference may be an issue only in evacuation times exceeding several hours. It should be noted that a further refinement in the HPMK has been made to improve the product, which should continue to make it a valuable option for reducing heat loss.

This study should be repeated in a biological model to validate these results. Additional investigation is also needed to determine whether devices with an actively heated component cause thermal burns in patients. Taken together, this study will serve as a guide to providers for selecting a hypothermia prevention system. Although the study was designed for evaluating products available in the US Army supply system, the results should be applicable to all first responders, whether military or civilian, who are concerned with preventing further heat loss in trauma patients.

ACKNOWLEDGMENTS

We thank Briza Horace for assistance in the preparation of this article and John Jones for assistance in the statistical analysis. In addition, we thank Kelly Thompson and Dominique Greydanus for their support in helping us accomplish this study.

REFERENCES

1. Taguchi A, Kurz A. Thermal management of the patient: where does the patient lose or gain temperature. *Curr Opin Anaesthesiol.* 2005;18:632–639.
2. Danzl D. Hypothermia. *Semin Respir Crit Care Med.* 2002;23:57–68.
3. Herr RD, White GL Jr. Hypothermia: threat to military operations. *Mil Med.* 1991;156:140–144.
4. Farkash U, Lynn M, Scope A, et al. Does pre-hospital fluid administration impact core body temperature and coagulation functions in combat casualties? *Injury.* 2002;33:103–110.
5. Carr ME Jr. Monitoring of hemostasis in combat trauma patients. [Review]. *Mil Med.* 2004;169(12 Suppl):11–15, 4.
6. Holcomb J. The 2004 fitts lecture: current perspective on combat casualty care. *J Trauma.* 2005;59:990–1002.
7. Beilman GJ, Blondet JJ, Nelson TR, et al. Early hypothermia in severely injured trauma patients is a significant risk factor for multiple organ dysfunction syndrome but not mortality. *Ann Surg.* 2009;249:845–850.
8. MacLeod JB, Lynn M, McKenney MG, Cohn SM, Murtha M. Early coagulopathy predicts mortality in trauma. *J Trauma.* 2003;55:39–44.
9. Hammond KL, Margolin DA. Surgical hemorrhage, damage control, and the abdominal compartment syndrome. *Clin Colon Rectal Surg.* 2006; 19:188–194.
10. Insler SR, Sessler DI. Perioperative thermoregulation and temperature monitoring. [Review]. *Anesthesiol Clin.* 2006 Dec; 24(4):823–837.
11. 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(6 Suppl):S3–S11.
12. Eastridge BJ, Malone D, Holcomb JB. Early predictors of transfusion and mortality after injury: a review of the data-based literature. [Review]. *J Trauma.* 2006;60(6 Suppl):S20–S25.
13. Eiseman B, Moore EE, Meldrum DR, Raeburn C. Feasibility of damage control surgery in the management of military combat casualties. *Arch Surg.* 2000;135:1323–1327.
14. Kauvar DS, Holcomb JB, Norris GC, Hess JR. Fresh whole blood transfusion: a controversial military practice. *J Trauma.* 2006;61:181–184.
15. Aragon D. Temperature management in trauma patients across the continuum of care: the TEMP Group. Temperature Evaluation and Management Project. *AACN Clin Issues.* 1999;10:113–123.
16. McDonald V, Ryland K. Coagulopathy in trauma: optimizing haematological status. *Trauma.* 2008;10:109–123.
17. Marshall TJ Jr. Combat casualty care: the Alpha Surgical Company experience during Operation Iraqi Freedom. *Mil Med.* 2005;170:469–472.
18. Gamble WB. Recent advances made in wartime medical care. *J Craniofac Surg.* 2006;17:1033–1034.
19. Eastridge BJ, Owsley J, Sebesta J, et al. Admission physiology criteria after injury on the battlefield predict medical resource utilization and patient mortality. *J Trauma.* 2006;61:820–823.
20. Knappe T, Mittlmeier T, Eipel C, Amon M, Menger MD, Vollmar B. Effect of systemic hypothermia on local soft tissue trauma-induced microcirculatory and cellular dysfunction in mice. *Crit Care Med.* 2005;33:1879–1881.
21. Arthurs Z, Cuadrado D, Beekley A, et al. The impact of hypothermia on trauma care at the 31st combat support hospital. *Am J Surg.* 2006;191: 610–614.
22. Beekley AC, Watts DM. Combat trauma experience with the United States Army 102nd Forward Surgical Team in Afghanistan. *Am J Surg.* 2004;187:652–654.
23. Moritz A, Henriques F. Studies of thermal injury: II. The relative importance of time and surface temperature in the causation of cutaneous burns. *Am J Pathol.* 1947;23:695–720.

DISCUSSION

Dr. Daniel Darlington (US Army Institute of Surgical Research, Fort Sam Houston, TX): I would like to thank the USAISR for giving me an opportunity to comment on the authors' study of an in vitro torso model constructed with fluid bags for use to differentiate between the heat prevention performance of devices with active chemical or radiant forced-air heating systems compared with passive heat loss prevention devices.

I shall comment on the abstract first, then on the specific sections of the text.

Nothing in the results of the abstract leads to the conclusion that passive blankets can be used effectively at room temperature. The authors may need to state in the "Methods" of the abstract that all blankets were stored before use at room temperature. This may also need to be stated in the "Methods" section.

In the "Introduction," I find the following sentence confusing: "Do passive heat loss prevention systems prevent heat loss during 120 minutes that are comparable with systems with an actively heated component?" May I suggest, "Are passive heat loss systems as good or better at preventing heat loss when compared with actively heated systems" or something like this?

For the Results section, I have the following questions:

1. Active Groups: Is there any significant difference between active groups? Are all active groups different from control?
2. Figure 1 (and possible all others) needs to be expanded (say *y* axis; range, 32–40°C) so that we can see similarities or differences in the data.

3. Hypothermia Prevention Management Kit (HPMK)

Methods: "The kit was wrapped in sequence, heating blanket over anterior surface, reflective shell over heating blanket, and sealed according to its recommended use."

Is the heating blanket the "ready heat" and the reflective shell the "Heat Reflective Shell" or Blizzard (?) described above in the methods. This description is confusing.

4. Figure 2 needs to have *y* axis expanded (range, 32–40°C or better). It is impossible to see how each passive blanket compares. Are there significant differences between passive blankets? Which one performed better?
5. Maybe helpful to state at the end of each blanket description whether or not the performance of the blanket was statistically better than the control (or no blanket). Some descriptions have it and some do not. Be consistent.

In the Discussion section, you state, "The original HPMK maintained the highest temperatures compared with all other methods." HPMK was only compared with its components? Was it compared with the passive systems? Looking at figures 1 and 2 suggests that some of the passive systems may not be different from HPMK.

Overall, the graphs tell me little. Increase the range on the *y* axis so that the reader can actually see the data.

Where is the comparison (or statistics) between the active and passive blankets? Was not this comparison one of the objectives in the "Introduction?"

May I suggest a table that contains the 30-minutes, 60-minutes, and 120-minutes temperatures for all blankets. Then compare them statistically so that the reader can see them and you can satisfy Objective 2 in the "Introduction."

Most of your conclusion can be placed in the Discussion section. Make a definitive conclusion based on the Objectives (as written below).

1. Are devices with active chemical or radiant-forced air heating systems better than passive prevention of heat loss?
2. Do passive heat loss prevention systems prevent heat loss during 120 minutes that are comparable with systems with an actively heated component?
3. Do any of the devices with an actively heated component achieve temperatures known to cause burns on human skin?

Dr. Michael A. Dubick (US Army Institute of Surgical Research, Fort Sam Houston, TX): Thank you for your comments. You have raised some good points about the abstract. We have now revised the conclusion of the abstract and have added that blankets were kept at room temperature before testing.

In the "Introduction," we have made the following revisions based on your comments: We have deleted the acronym, CASEVAC, and have clarified our statement regarding the comparison between passive and active warming systems.

In the Results section, we have now indicated whether there were any significant differences among the active warming devices tested and whether they differed from control. We have also expanded the *y* axis as suggested to reflect our discussion of the data better.

Hypothermia Prevention Kit: (1) To clarify, the Ready Heat is the heating blanket, and the reflective shell is the Heat Reflective Shell to differentiate it from the Blizzard, which was the other reflective shell component in the original HPMK tested. We have clarified this in the text. (2) and (3) As indicated in (3) above, we have expanded the *y* axis label. (4) We have considered the reviewer's request and have revised the text to be more consistent in indicating which devices were statistically different from control.

Discussion section: (1) We were mentioning that the original HPMK maintained the highest temperatures and did compare with other products, including the passive ones. We have revised the text to clarify this point. (2) As mentioned in (3) above, we have revised the graphs to expand the *y* axis so that the reader can see differences more clearly. (3) The text has been revised to include comparisons between the active and passive devices. (4) We revised Table 1 to include statistical comparisons.

Conclusion: (1) We have taken the reviewer's advice and have revised the conclusion to be more precise. (2) Again the conclusion has been revised to address the comparison between active and passive warming systems and to clarify which passive systems seemed just as good as active warming devices in maintaining temperature during the 120 minutes experimental period. (3) We have also previously mentioned in the text that none of the active warming devices produced high enough surface temperatures that have been shown previously to directly burn human skin. We added a statement in the "Discussion" to provide more information regarding this point.