AFRL-RH-WP-TR-2020-0011

PERFORMANCE
CHARACTERISTICS OF FLUID WARMING
TECHNOLOGY IN AUSTERE ENVIRONMENTS

Thomas C. Blakeman

30 July 2019

Distribution A: Approved for public release; distribution is unlimited. Case Number: 88ABW-2020-1086, 19 Mar 2020

Air Force Research Laboratory
711th Human Performance Wing
C-STARS Cincinnati
2510 Fifth St.
Wright-Patterson AFB, OH 45433-7913

NOTICE AND SIGNATURE PAGE

AFRL-RH-WP-TR-2020-0011HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

//SIGNATURE//

____

TAMERA G. BORCHARDT, Lt Col, NC
Branch Chief, Biomedical Impact of Flight

//SIGNATURE//

____

GUY R. MAJKOWSKI, Col, BSC
Division Chief, Warfighter Medical Optimization

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* 30-07-2019	**2. REPORT TYPE** Final Report	**3. DATES COVERED *(From – To)*** 27 Jun 2016 – 26 April 2019

4. TITLE AND SUBTITLE Performance Characteristics of Fluid Warming Technology in Austere Environments	**5a. CONTRACT NUMBER** **FA8650-15-2-6605** **5b. GRANT NUMBER** FA8650-16-2-6G10 **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) Thomas Blakeman Dario Rodriquez, Jr Richard Branson John Fowler Victor Heh	**5d. PROJECT NUMBER** 16-006 **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Cincinnati Sponsored Research Services 51 Goodman Drive, Suite 530 Cincinnati, OH 45221-0222	**8. PERFORMING ORGANIZATION REPORT NUMBER** AFRL-RH-WP-TR-2020-0011
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory 711 HPW/RHM C-STARS Cincinnati 2510 Fifth St. Wright-Patterson AFB, OH 45433-7913	**10. SPONSORING/MONITOR'S ACRONYM(S)** **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION / AVAILABILITY STATEMENT

Distribution A: Approved for public release; distribution is unlimited. Case Number: 88ABW-2020-1086, 19 Mar 2020

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Background: Resuscitation of the critically ill/injured is a vital and complex task in any setting, often compounded by environmental influences in austere environments. The need for equipment to support this function is paramount and the devices used must provide reliable performance meeting clinician expectations for intended use. In the setting of resuscitation, some devices used for infusions are also designed to warm fluids. We evaluated four portable, battery powered fluid warmers to determine the ability to warm fluids at different flow rates.
Methods: We evaluated fluid warmers currently employed and/or under procurement consideration; Buddy Liter and Buddy Lite AC, (Belmont Instrument Corp., Billerica, MA), Thermal Angel, (Estill Medical Technologies, Dallas, TX), and M Warmer, (MEQU, Copenhagen, DK). Using standard IV tubing attached to a room temperature (23-24oC), 1000 mL bag of 0.9% NaCl solution, each device was attached to the distal end of the tubing. Fluid temperature was measured via a thermocouple (Compact DAQ, National Instruments, Austin, TX) before entering the device and after flowing through the device at the end of an IV extension tubing, simulating the point at which the fluid would enter a patient's circulation. Temperature was measured every second and recorded to a computer for later analysis. Two flow rates were utilized for testing with each device. One hundred twenty-five mL/hr was used to simulate a non-emergent maintenance rate for 1 hour and was controlled with an IV pump. An emergent rate was simulated by placing a 1000 mL bag of NaCl in a pressure infusion bag inflated to 300 mm/Hg, allowing the fluids to free flow under pressure through the device. Two of each device was used for the evaluation with two tests accomplished at each flow rate at ground level, 8,000 and 16,000 ft altitude.
Results: Mean fluid temperatures varied between the different devices and within the same device types. Data was averaged over all tests with each device type. None of the devices were able to heat normal saline or cold PRBC to a mean temperature equal to normal human body temperature (37oC) at either flow rate tested. Analysis of the differences in overall temperature profiles produced by the devices at all conditions was statistically significant ($p < 0.01$) except for the Buddy Liter vs the Buddy Lite at ground level on AC power, at the non-emergent flow rate using room temperature normal saline ($p = 0.42$), and the same devices at 16,000 ft altitude on AC power at the non-emergent rate, using cold PRBC ($p = 0.24$). Differences in mean temperature between devices at the non-emergent flow rate using both normal saline and PRBC were within 3o C at each of the altitude conditions, although the temperatures where somewhat lower at altitude as compared to ground level. The M Warmer produced mean fluid temperatures ≥ 35o C at least 80% of the testing time at the emergent rate using normal saline and PRBC and was significantly higher than the other devices, at all altitudes.
Conclusion: In our evaluation, fluid flow rate had an impact on the temperatures attained by the devices. At the non-emergent and emergent flow rates, none of the devices were able to warm the fluids to a mean temperature 37oC. The M Warmer clearly outperformed the other devices at the emergent rate with PRBC and normal saline. Understanding the performance characteristics of fluid warming devices and their role in management of resuscitation is vital for the caregiver especially in austere environments.

15. SUBJECT TERMS

Fluid Warmers

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** James B. Lehman
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	SAR	21	**19b. TELEPHONE NUMBER *(include area Code*** 513-558-7462

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

This page intentionally left blank.

TABLE OF CONTENTS

Section

1.0 INTRODUCTION

2.0 METHODS

3.0 STATISTICAL ANALYSIS

4.0 RESULTS

5.0 DISCUSSION

6.0. LIMITATIONS

7.0 CONCLUSIONS

8.0 REFERENCES

9.0 TABLES AND FIGURES

1.0 Introduction:

Resuscitation of the critically ill/injured is a vital and complex task in any setting, often compounded by environmental influences. Hypothermia is one of the components of the “Triad of Death” in trauma patients, frequently seen in the prehospital setting,1 and exacerbated by the resuscitation efforts.2-4 Studies have shown that the incidence of hypothermia in the prehospital setting can reach 43%.5 Most guidelines classify hypothermia as mild, 35oC to 32oC; moderate, 32oC to 28oC; or severe, <28oC.6-9 Warming of intravenous (IV) fluids is recommended for the mitigation/treatment of hypothermia in prehospital trauma patients.10 The U.S. military has many of the same needs as civilian prehospital caregivers but operates under unique conditions. Many casualties require fluid resuscitation and simultaneous treatment of hypothermia in the field. Far forward deployed military units do not have ability to warm large quantities of IV fluids due to weight and cube constraints11. Devices for warming IV fluids in this environment must be small and portable, able to operate on battery power, warm fluids to normal body temperature (37oC), and perform under various conditions including at altitude. We evaluated 4 portable fluid warmers that are already fielded or that could be used in the military prehospital environment...

2.0. Methods:

The study evaluated four portable fluid warming devices: Buddy Liter and Buddy Lite AC (Belmont Instrument Corp., Billerica, MA), Thermal Angel (Estill Medical Technologies, Dallas, TX), and M Warmer (MEQU, Copenhagen, DK). These devices are shown in figure 1. The devices were evaluated using two different fluids and flow rates. Room temperature normal saline (NS) was run at a non-emergent rate of 125 mL/hr (2.1 mL/min) for 1 hour via an Alaris Medsystem III infusion pump (Becton, Dickinson and Company, Franklin Lakes, NJ), and also using a pressure bag inflated to 300 mm Hg to represent an emergent rate, infusing one liter of fluid. These flow rates were chosen as extremes that may be encountered in far forward and transport military operations based on experience of one of the authors (JF). During high flows under pressure, flow was calculated by infusing a measured 1-liter volume of normal saline, running the fluid through each warmer using the pressure bag, and measuring the time in seconds to infuse the fluid. Flow rates for the Buddy Liter, Buddy Lite, M Warmer, and Thermal angel were 278 mL/min, 278 mL/min, 222 mL/min, and 232 mL/min respectively.

Expired, iced-packed red blood cells (PRBC) were run under identical conditions as the normal saline with the exception of using two units of PRBC infused simultaneously at the emergent rate instead of 1 liter. These tests were done at ground level and at 8,000 and 16,000 feet simulated altitude in an altitude chamber. The ambient chamber inside the altitude chamber was maintained at 24o C to approximate the ambient temperature in our laboratory (23.9 ± 0.4o C) where ground level testing was completed. Two of each device were used in the study and two tests with each device were completed at each condition. All devices were operated on battery power and the Buddy Liter and Buddy Lite AC were also operated on AC power. The Thermal Angel and M Warmer do not offer the option of operating from AC power.

The devices were set up per manufacturer's instructions. The infusion pump had preventive maintenance and calibration performed before the study began. Device batteries were charged for a minimum of 24 hours before use. Standard IV tubing was used for all non-emergent flow rates with the infusion pump and with pressure bag and standard blood tubing was used for testing with PRBC. A 3-way stopcock placed at the entrance to and directly after the heater unit of the device being tested and a J-type thermocouple (Omega Engineering, Norwalk, CT) was placed in each of the stopcocks open port and sealed with silicone. The thermocouples were attached to a data acquisition system (National Instruments, Austin, TX) and temperature data were continuously recorded at 1-second intervals. The Buddy Liter and Buddy Lite utilize disposable cartridges inside the reusable heater unit and the Thermal Angel and M Warmer utilize disposable heater units. All the cartridges/heater units except the Thermal Angel had tubing before and after the heater units. These are the points at which the pre-heater and post-heater temperatures were measured. A 9-inch IV extension tubing supplied with the Thermal Angel was placed on the output side of the heater in order for measurements to be taken in the same location with all devices and would simulate the temperature at which the warmed fluid would enter a patient's circulation. After priming, each warmer was turned on and fluid flow and temperature measurements were started simultaneously.

The measurements of interest for this study were mean temperature, time to reach mean temperature, change in temperature from inlet to outlet, and proportion of time the temperature was ≥ 32.o C and ≥ 35o C.

3.0 Statistical Analysis:

Temperature differences at specified conditions: Normal saline and PRBC, emergent flow rate and non-emergent flow rate, and altitude differences were compared for each device. Mean and standard deviation were used to summarize data. Comparisons were made using the General Linear model univariate analysis to create contrasts that tested specified custom hypotheses. This method was preferred in order to avoid testing all pairwise comparisons as comparisons were set a priori. Post hoc analysis was completed by comparing the change in temperature pre-warmer to post warmer and time to reach mean temperature created with each device at all conditions using a Student's t-test. Devices were compared to each other at all conditions and compared to themselves using altitude as the independent variable to determine if altitude had an effect on device performance. Statistical significance was determined at alpha of 0.05, two-tailed and SPSS version 25 was used for data analysis.

4.0 Results:

Table 1 shows the physical and operational characteristics of the devices. There was no distinct size or weight advantage of one device over the others, demonstrating that all the devices were portable. The stated maximum flow rates were much higher for the Thermal Angel and M Warmer. None of the devices were able to heat normal saline of cold PRBC to a mean temperature equal to normal human body temperature (37oC) at either flow rate tested. Analysis of the differences in overall temperature profiles produced by the devices at all conditions was statistically significant ($p < 0.01$) except for the Buddy Liter vs the Buddy Lite at ground level on AC power, at the non-emergent flow rate using room temperature normal saline ($p = 0.42$), and the same devices at 16,000 ft altitude on AC power at the non-emergent rate, using cold PRBC ($p = 0.24$). Figure 2 shows the mean (SD) temperatures for all devices on battery power. The M Warmer produced the highest mean temperatures at the emergent flow rate using normal saline and cold PRBC. Differences in mean temperature between devices at the non-emergent flow rate using both normal saline and PRBC were within 3oC at each of the altitude conditions, although the temperatures where somewhat lower at altitude as compared to ground level. Figure 3 shows the mean (SD) temperatures for the Buddy Liter and Buddy Lite on AC power. The Buddy Lite produced the highest mean temperature at the emergent flow rate using saline and PRBC.

Data comparing each of the devices with the change in fluid temperature from before entering the device and after leaving the warmer at the end of the extension tubing plus the time the devices took to reach the mean temperature produced by the devices at all conditions are shown in table 2. The table also shows the device pairings that had statistically significant differences denoted by symbols next to the data. The temperature changes varied widely between devices and to a lesser degree, the time to reach mean temperature. Nearly all the changes in temperature between devices were statistically significant at the emergent rate using both normal saline and PRBC as were nearly 50% of the time to reach mean temperature at the emergent rate.

Using battery power, the proportion of time as a percentage, that the temperature was ≥ 35o C was less 1% with the M Warmer with the cold PRBC at ground level only. At 8,000 ft and 16,000 ft the temperature produced with the device did not reach 35o C. None of the other devices were able to produce this temperature using cold PRBC at any altitude. The percentage of time the Buddy Liter, Buddy Lite, and M Warmer reached this threshold using normal saline, non-emergent flow rate, at ground level was 61%, 41%, and 65% respectively. Temperatures did not reach the ≥ 35o C threshold at 8,000 and 16,000 ft. The Thermal Angel did not reach this threshold at ground level or any altitude. Using normal saline and PRBC at the emergent rate, only the M Warmer had any significant percentage of time at ≥ 35o C. The percentage of time above this threshold was 96%, 81%, and 80% at ground level, 8,000 ft, and 16,000 ft respectively.

Figure 4 shows the percentage of time the devices produced temperatures ≥ 32o C at all conditions on battery power. As shown, the percentage of time the M Warmer produced fluid temperatures that reached this threshold was significantly higher than the other devices using normal saline and PRBC at the emergent rate, at all altitudes. The Buddy Liter and Buddy Lite failed to produce temperatures that reached this threshold at any altitude. At ground level using normal saline at the non-emergent rate, all the devices reached this threshold > 90% of the time.

At this condition, percentages above this threshold were significantly less for all devices at 8,000 ft and 16,000 ft except for the Thermal Angel at 8,000 ft (97%). At ground level using PRBC at the non-emergent rate, all devices except the Thermal angel reached the ≥ 32o C threshold > 90% of the time. At 8,000 ft and 16, 000 ft the percentage of time at the threshold was less.

The Buddy Liter and Buddy Lite were the only two devices that had the capability to use AC power in addition to battery power so this data was analyzed separately. Nearly all the differences in changes in temperature between these two devices were statistically significant and less than half of the time to mean temperature differences were significant. The majority of the significant differences were when comparing ground level to 16,000 ft altitude. (data not shown).

5.0 Discussion:

This study showed there were large differences in the temperature profiles between devices on battery power, using emergent flow rate with both normal saline and PRBC. There were also differences among devices using non-emergent flow rate, although much smaller (figure 2). The M Warmer produced the highest mean temperature at all conditions. The change in temperature from the inlet of the warmers to the end of the outlet extension tubing was used to determine the devices heating ability and is a more accurate indicator of performance due to the differences in the time to warm the fluids to the mean temperature.

Contrary to the study by Dubick et al12, time to mean fluid temperature was not a good indicator of device performance due to inconsistencies with change in temperature within each device type and between devices.

This may be due to the very low and high flows used in the present study. The M Warmer consistently produced the highest mean temperature and temperature change but often did not have the fastest time to mean temperature. The reason for the consistencies could be attributed to the higher temperature change produced by the M Warmer which may have
resulted in a longer time to reach the mean temperature and the mean temperature was always higher than with the other devices.

Warming cold PRBC at the emergent flow rate and to a lesser degree, normal saline at the same flowrate clearly showed the differences in heating ability of the devices under extreme conditions. Temperature differences were not as great at the non-emergent flow rate which may be attributed to the flow rate (125 mL/hr) being sufficiently low that the temperature exiting the devices was cooled toward ambient temperature by the time the measurement was made at the end of the extension tubing on the exit side of the warmers. We did not measure the temperature immediately exiting the warmer due to lack of clinical relevance. We believe the fluid temperature at the point at which it would enter entering a patient's circulation is clinically relevant and therefore a better measure of capability.

A literature review revealed 3 relevant studies that evaluated battery operated, portable fluid warmer technology13-15. These studies included the Buddy Lite in the evaluations. Consistent with these studies, our study showed that the warming capability of the Buddy Lite decreased with increases in flow rate as did the Thermal Angel in studies performed by Weatherall et al13 and Dubick et al12. Dubick also found the device performance decreased significantly when using cold fluids at both high and low flow rates.

We chose the thresholds for the percentage of time that each device heated fluid to ≥ 32o C and ≥ 35o C based on work by Jurkovich et al16 and Dubick et al12. The authors reported a 40% mortality in trauma patients if core temperature was < 34o C, 69% if core temperature was < 33o C, and 100% if core temperature was < 32o C. Based on this data, the ideal goal for fluid of the time at the emergent rate using both normal saline and PRBC, which were the most challenging conditions. This is an important finding in that core body temperature decreases approximately 0.25o C for every unit of cold PRBC and every liter of ambient temperature fluids administered17 and maintaining/increasing core body temperature is an important consideration with fluid administration. We chose the threshold of ≥ 32o C as the absolute acceptable minimum for 2 reasons: Core temperature < 32o C is when shivering, the human body's mechanism for raising core temperature ceases18,19, plus the reported mortality rate below this threshold is 100%. The Buddy Liter and Buddy Lite failed to reach this threshold using normal saline at the emergent flow rate and reached it < 15% of the time using PRBC at the emergent rate (Fig 4).

Temperatures produced by the warmers using the non-emergent flow rate of 125 mL/hr were lower than expected especially when warming cold PRBC. This can be attributed to the slow flow rate (~2 mL/min) allowing the fluid to cool toward room temperature after exiting the warmer while flowing through the extension tube to the post-warmer temperature measurement. The extension tubing provided with the warmers was a minimum of 15 cm in length. The minimum reported tubing length to maintain post-warmer fluid temperature > 32o C is < 10 cm18.

Utilizing the shortest IV tubing possible between the warmer and the patient may help to increase the delivered fluid temperature.warmers should be to deliver fluid temperatures > 34o C, therefore we chose the threshold of ≥ 35o C. The M Warmer was the only device we tested that was able to reach this threshold ≥ 80%

6.0 Limitations:

Per operator's manuals, maximum output temperature for the devices vary: Buddy Liter and Buddy Lite were 38 ± 2o C; Thermal Angel was 38 ± 3o C; M Warmer was 39 ± 3o C. The devices lack a temperature readout so there was no way of knowing the actual operating temperature for each test condition. The emergent flowrate using a pressure bag was greater than the maximum flowrate published for each device, but this method of rapidly infusing fluids or PRBC is common practice in the face of resuscitation following hemorrhage and would likely be encountered in clinical practice. The accuracy of the thermocouples and the data acquisition system was 0.9o C and 1o C respectively which may explain some of the differences in temperature although the same thermocouples and data acquisition system were used for the entire study so any variation in measurement was consistent throughout the evaluation.

7.0 Conclusions:

Although none of the devices warmed fluids to normal body temperature (37o C), likely due to the high flows used, the M Warmer was the only warmer tested that heated normal saline and PRBC to ≥ 32o C and PRBC to ≥ 35o C more than 80% of the time at the emergent flow rate. The M Warmer and in some cases the Thermal Angel performed better at the higher flow rate whereas the Buddy Liter and Buddy Lite did not. Altitude appeared to have a small effect on the output temperatures in some testing scenarios but the differences were not clinically important. Future evaluation of the devices at altitude, within the documented operational flow rate range for each device may show more accurate warming differences at altitude.

8.0 References:

1. Mitra B, Tullio F, Cameron PA, Fitzgerald M. Trauma patients with the "triad of death". Emerg Med J 2012;29(8):622-625. doi:10.1136/emj.2011.113167

2. Garcia GD, Modesto VL, Lee KT. Avoiding hypothermia in trauma: use of the flawless heater pack, meal ready to eat, as a field-expedient means of warming crystalloid fluid. Mil Med 2000;165(12):903-904,

3. Nolan JP, Dow AAC. The Level 1 fluid warmer. Anaesthesia 1991;46(4):318-319.

4. Handrigan MT, Wright RO, Becker BM, et al. Factors and methodology in achieving ideal delivery temperatures for intravenous and lavage fluid in hypothermia. Am J Emerg Med 1997;15(4):350-353.

5. Bielman GJ, Blondet JJ, Nelson TR, Nathens AB, Moore FA, Rhee P 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(5):845-850.

6. Durrer B, Brugger H, Syme D. International Commission for Mountain Emergency Medicine. The medical on-site treatment of hypothermia: ICAR-MEDCOM recommendation. High Alt Med Biol 2003;4(1):99-103.

7. Soar J, Perkins GD, Abbas G, et al. European Resuscitation Council Guidelines for Resuscitation 2010 Section 8. Cardiac arrest in special circumstances: electrolyte abnormalities, poisoning, drowning, accidental hypothermia, hyperthermia, asthma, anaphylaxis, cardiac surgery, trauma, pregnancy, electrocution. Resuscitation 2010; 81:1400-143.

8. Danzl D. Accidental hypothermia. In:Auerbach PS, ed. Wilderness Medicine 6th ed. Philadelphia, PA: Elsevier;2012:116-142.

9. Zafren K, Giesbrecht G. State of Alaska Cold Injury Guidelines, Juneau, AK: State of Alaska; 2014.

10. Zafren K, Giesbrecht GG, Danzl DF, Brugger H, Sagalyn EB, Walpoth B et al. Wilderness medical society practice guidelines for the out-of-hospital evaluation and treatment of accidental hypothermia.Wilderness Environ Med 2014;25(4):425-445.

11. Garcia GD, Modesto VL, Lee KT. Avoiding hypothermia in trauma: use of the flameless heater pack, meal ready to eat, as a field-expedient means of warming crystalloid fluid. Mil Med 2000;165(12):903-9.4.

12. Dubick MA, Brooks DE, Macaitis JM, Bice TG, Moreau AR, Holcomb JB. Evaluation of commercially available fluid-warming devices for use in forward surgical and combat areas. Mil Med 2005;170(1):76-82.

13. Weatherall A, Gill M, Milligan J, Tetlow C, Harris C, Garner A, Lee A. Comparison of portable blood-warming devices under simulated pre-hospital conditions: a randomised in-vitro blood circuit study. Anaesthesia 2019;74(8):1026-1032.doi:10.1111/anae.14680.

14. Lehavi A, Yitzham A, Jarassy R, Heizler R, Katz Y, Raz A. Comparison of the performance of battery-operated fluid warmers. Emerg Med J 2018;35(9):564-570.

15. Kim HJ, Yoo SM, Jung JS, Lee SH, Sun K, Son HS. The laboratory performance of the enFLOW, buddy lite, and Thermosens fluid warmers. Anaesthesia 2015;70(2):205-208.

16. G.J. Jurkovich, W.B. Greiser, A. Luterman, P.W. Curreri. Hypothermia in trauma victims: an ominous predictor of survival. J Trauma 1987;27(9):1019-1024.

17. Sessler DI. Mild perioperative hypothermia. NEJM 1997;336(24):1730-1737.

18. Faries G, Johnston C, Pruitt KM, Plouff RT. Temperature relationship to distance and flow rate of warmed i.v. fluids. Ann Emerg Med 1991;20(11):1198-2000.

19. Tikuisis P, Giesbrecht GG. Prediction of shivering heat production from core and mean skin Temperatures. Eur J Appl Physiol Occup Physiol 1999;79(3):221-229.

9.0 Figures and Tables

	Buddy Liter	Buddy Lite AC	Thermal Angel	M Warmer
Dimensions (in)(LxWxH) Battery housing Heater unit	 4.92 x 3.33 x 1.36 5.2 x 1.5 x 0.87	 7.26 x 3.33 x 1.36 15.2x 1.5 x 0.87	 6.4 x 3.2 x 1.7 9 x 2.9 x 0.95	 7.09 x 3.54 x 1.38 3.94 x 1.97 x 0.79
Weight (lbs) Battery & heater unit AC power supply	 1.09 2.64	 1.46 2.64	 1.83 N/A	 1.68 0.55
Power requirement	AC, battery	AC, battery	Battery	Battery
Temp set point (°C)	38 ± 2	38 ± 2	38 ± 3	39 ± 3
High temp alarm	Aural & Visual	Aural & Visual	Visual	Visual
Low temp/no heat alarm	Aural & Visual	Aural & Visual	Visual	Visual
Max flow rate (mL/min)	30 @ 20°C 20 @ 10°C	80 @ 20°C 50 @ 10°C	150 @ 20°C	150 @ 4°C – 37°C

Table 1. Physical and operational characteristics for each fluid warming device.

	RT NS SL	RT NS 8K	RT NS 16K	Cold PRBC SL	Cold PRBC 8K	Cold PRBC 16K
Emergent Flow Rate						
Time to reach mean temp at end of outlet tubing (sec)						
Buddy Liter - powered	26 ± 19	20 ± 3	10 ± 2	151 ± 31	42 ± 27	119 ± 32†
Buddy Liter - battery	30 ± 6 ‡†	23 ± 3 #‡	17 ± 16 ‡	108 ± 38 ‡ψ†	37 ± 14 †	94 ± 28 Δψ
Buddy Lite - powered	60 ± 11	49 ± 17	36 ± 20	91 ± 23	58 ± 17	55 ± 7
Buddy Lite - battery	32 ± 15 †	33 ± 4 Δ‡ψ	23 ± 2 ‡ ψ	103 ±16 ‡	62 ± 20 Δ‡	48 ± 13 ψ
Thermal Angel	47 ± 4	60 ± 13	58 ± 4 ψ	28 ± 13 ψ†	25 ± 3 †	61 ± 34
M Warmer	34 ± 20	24 ± 3 ‡	25 ± 2 ‡ ψ	68 ± 31 ψ	25 ± 12	27 ± 7 † ψ
Temp change from inlet to end of outlet tubing (°C)						
Buddy Liter - powered	2.4 ± 0.3 †	2.0 ± 0.2 †	1.8 ± 0.1	9.0 ± 0.3 †	13.5 ± 0.9 †	11.3 ± 1.0
Buddy Liter - battery	1.6 ± 0.2 #Δ‡†ψ	1.5 ± 0.2 #Δ‡†	1.4 ± 0.3 #Δ‡†ψ†	6.5 ± 0.8 #Δ‡†ψ	9.5 ± 2.0 Δ‡†	9.7 ± 1.5 Δ‡
Buddy Lite - powered	6.0 ± 0.3	4.7 ± 0.4	4.6 ± 0.6	18.0 ± 0.9	16.1 ± 1.6	8.6 ± 1.0
Buddy Lite - battery	4.5 ± 0.3 Δ‡ψ†	2.9 ± 0.7 Δ‡ ψ†	3.0 ± 0.2 Δ‡†	15.0 ± 0.5 Δ‡ψ†	13.4 ± 2.0 Δ	10.1 ± 0.9 Δ‡
Thermal Angel	7.9 ± 0.3 ψ†	6.1 ± 0.4 ψ†	6.7 ± 0.4†ψ	17.8 ± 0.8 ψ	15.0 ± 0.6	15.4 ± 0.3†ψ
M Warmer	12.7 ± 0.2 ‡ψ†	10.1± 0.6 ‡† ψ	9.9 ± 0.2 ‡ψ†	24.5 ± 0.8 ‡†ψ	22.5 ± 1.0 ‡†ψ	21.8 ± 1.2 ‡ψ†
Non-emergent Flow Rate						
Time to reach mean temp at end of outlet tubing (sec)						
Buddy Liter - powered	413 ± 71	246 ± 42	231 ± 45	252 ± 43	284 ± 43	296 ± 59
Buddy Liter - battery	252 ± 62	191 ± 38 ψ	270 ± 113	283 ± 48	281 ± 42	228 ± 90
Buddy Lite - powered	323 ± 59	207 ± 24	195 ± 65	273 ± 58	252 ± 81	336 ± 144
Buddy Lite - battery	206 ± 27 Δ‡ψ†	262 ± 105	235 ± 82 ‡	289 ± 25	237 ± 26	304 ± 37
Thermal Angel	244 ± 13 ψ	152 ± 29 ψ	133 ± 38	308 ± 61	324 ± 94	332 ± 55
M Warmer	251 ± 7 ψ	272 ± 66 ‡	259 ± 61	325 ± 99	345 ± 148	299 ± 155
Temp change from inlet to end of outlet tubing (°C)						
Buddy Liter - powered	9.6 ± 0.1	6.0 ± 0.3	6.8 ± 0.4	8.7 ± 0.7 †	5.6 ± 0.3 †	6.0 ± 0.9
Buddy Liter - battery	10.2 ± 0.3 ‡ψ	5.9 ± 0.4 Δ‡	6.9 ± 0.3 ‡	8.7 ± 0.7 ‡†	5.1 ± 0.7	6.9 ± 0.4 #‡†
Buddy Lite - powered	9.6 ± 0.1	5.8 ± 0.2	6.9 ± 0.2	9.0 ± 0.6	4.6 ± 0.3	5.3 ± 0.4
Buddy Lite - battery	9.7 ± 1.1	6.3 ± 0.4 ‡†	6.8 ± 0.6 ‡	8.7 ± 0.6 ‡ψ	5.5 ± 0.6 ‡	4.9 ± 0.1 Δ
Thermal Angel	8.5 ± 0.4 ψ†	8.4 ± 0.5 †ψ	8.5 ± 0.3 †ψ	6.7 ± 0.2 ψ†	4.3 ± 0.4 ψ	5.9 ± 0.9
M Warmer	10.3 ± 0.5 ‡	6.7 ± 0.7	6.4 ± 0.4 ‡†	9.1 ± 0.6 ‡	5.2 ± 0.6	7.0 ± 0.9 ‡†

Table 2. Temperature change from inlet of warmer to end of outlet tubing at all test conditions. Statistical significance ($p < 0.5$) legend: *vs Buddy Liter, #vs Buddy Lite, ‡vs Thermal Angel, Δvs M Warmer, ψvs Buddy Liter AC Power, †vs Buddy Lite AC Power.

Figure 1. The four devices evaluate in the study.

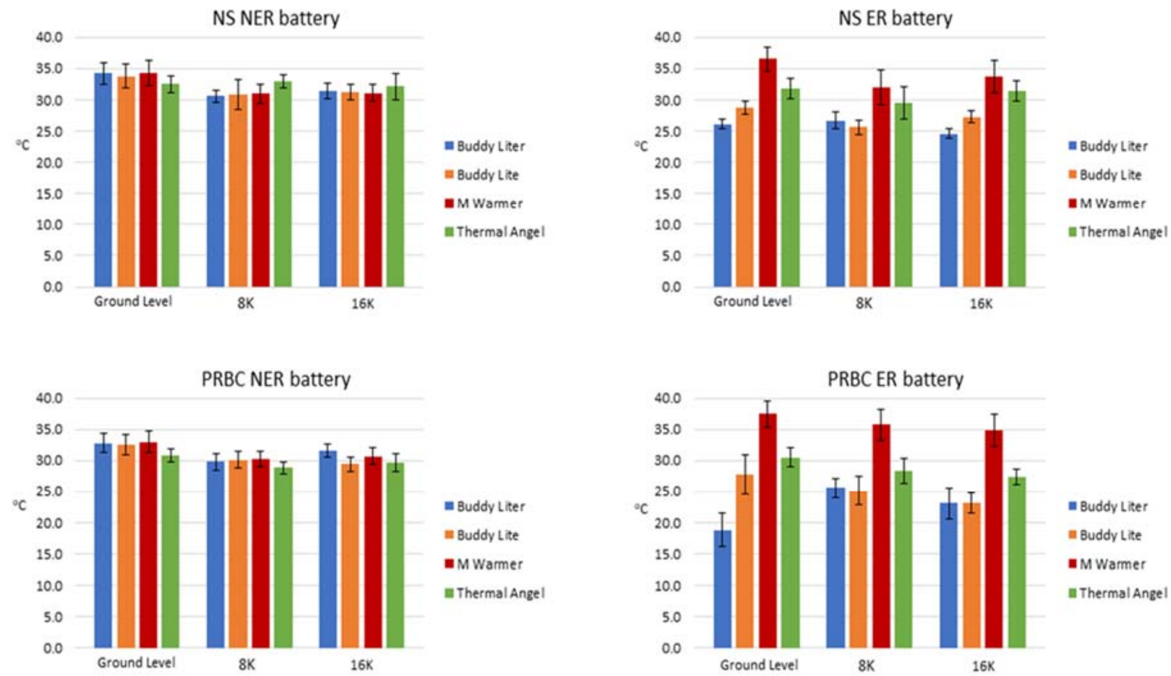

Figure 2. Mean (SD) temperatures for all devices on battery power. NS = normal saline, PRBC = packed red blood cells, NER = non-emergent rate, ER = emergent rate, ground level = ambient barometric pressure, 8K = 8,000 ft altitude, 16K = 16,000 ft altitude.

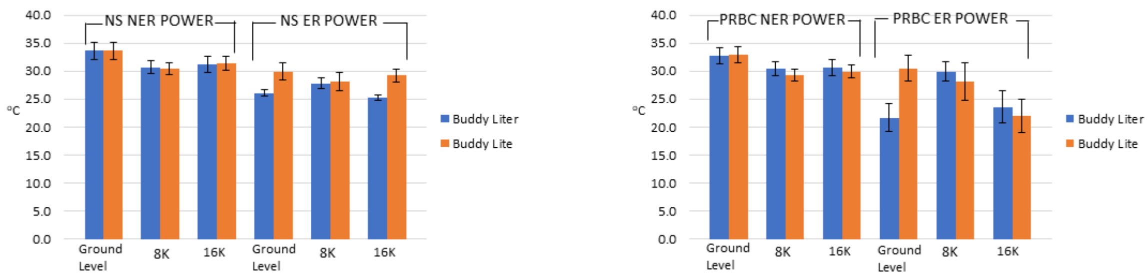

Figure 3. Mean (SD) temperatures for the Buddy Liter and Buddy Lite on AC power. NS = normal saline, PRBC = packed red blood cells, NER = non-emergent rate, ER = emergent rate, ground level = ambient barometric pressure, 8K = 8,000 ft altitude,16K = 16,000 ft altitude.

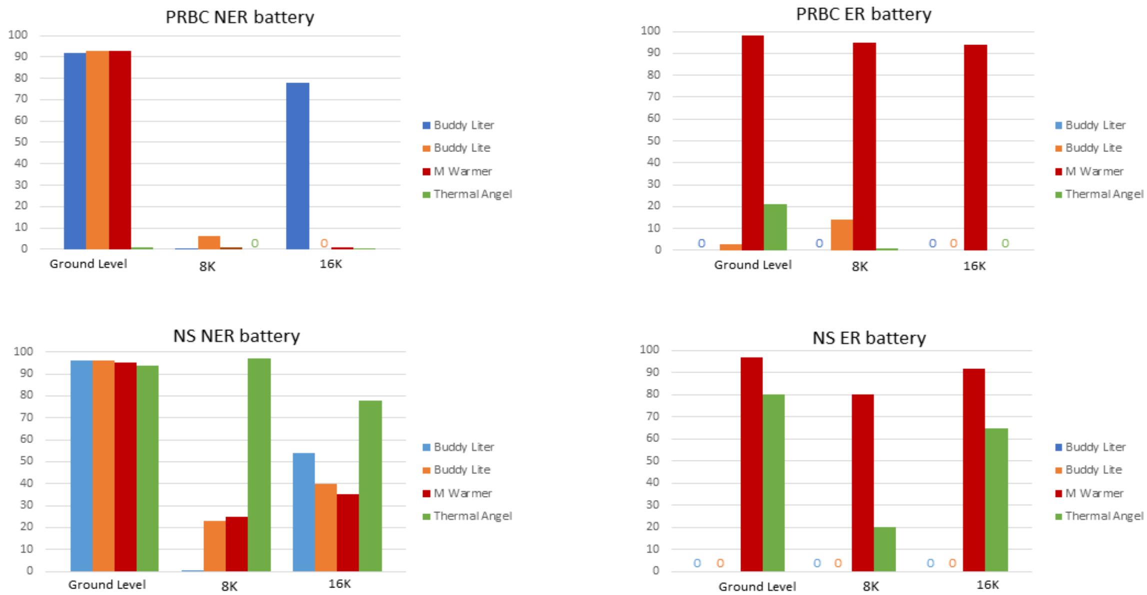

Figure 4. Proportion of time as a percentage that temperature at the end of the outlet tubing was ≥ 32ºC for all devices on battery power. NS = normal saline, PRBC = packed red blood cells, NER = non-emergent rate, ER = emergent rate, ground level = ambient barometric pressure, 8K = 8,000 ft altitude,16K = 16,000 ft altitude.