Air Medical Journal 38 (2019) 276–280

Contents lists available at ScienceDirect

Air Medical Journal

journal homepage: http://www.airmedicaljournal.com/

Original Research

Handheld Tissue Oximetry for the Prehospital Detection of Shock and Need for Lifesaving Interventions: Technology in Search of an Indication?

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A B S T R A C T

Improved prehospital methods for assessing the need for lifesaving interventions (LSIs) are needed to gain critical lead time in the care of the injured. We hypothesized that threshold values using prehospital handheld tissue oximetry would detect occult shock and predict LSI requirements. This was a prospective observational study of adult trauma patients emergently transported by helicopter. Patients were monitored with a handheld tissue oximeter (InSpectra Spot Check; Hutchinson Technology Inc, Hutchinson, MN), continuous vital signs, and 21 laboratory measurements obtained both in the field with a portable analyzer and at the time of admission. Shock was defined as base excess ≥ 4 or lactate > 3 mmol/L. Eighty-eight patients were enrolled with a median Injury Severity Score of 16 (interquartile range, 5-29). The median hemoglobin saturation in the capillaries, venules, and arterioles (StO_2) value for all patients was 82% (interquartile range, 76%-87%; range, 42%-98%). StO_2 was abnormal (< 75%) in 18 patients (20%). Eight were hypotensive (9%) and had laboratory-confirmed evidence of occult shock. StO_2 correlated poorly with shock threshold laboratory values ($r = -0.17$; 95% confidence interval, −0.33 to 1.0; $P = .94$). The area under the receiver operating curve was 0.51 (95% confidence interval, 0.39-0.63) for $StO_2 < 75\%$ and laboratory-confirmed shock. StO_2 was not associated with LSI need on admission when adjusted for multiple covariates, nor was it independently associated with death. Handheld tissue oximetry was not sensitive or specific for identifying patients with prehospital occult shock. These results do not support prehospital StO_2 monitoring despite its inclusion in several published guidelines.

Bleeding patients die fast. Even among those who survive at least 15 minutes after admission to a trauma center or a forward deployed military medical facility, half of those who will die from bleeding are dead within an hour, 60% within 2 hours, and 80% within 6 hours.[1,2] Valid, robust, and reliable prehospital methods for assessing the severity of hemorrhagic shock is paramount for effective triage and resource allocation with trauma patients. Current point-of-care testing modalities are limited in the realm of rotary wing air medical evacuation both for durability and weight considerations as well as reliability and effectiveness.

Tissue oximetry is a technology that allows for the measurement of hemoglobin saturation in the capillaries, venules, and arterioles

Supported by a grant from the Department of Defense, Air Force Research Laboratories (grant no. FA8650-15-2-6H01).

Acknowledgment: The authors would like to thank the women and men of the Maryland State Police Aviation Command for their assistance with this study.

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1067-991X/$36.00

https://doi.org/10.1016/j.amj.2019.03.014

(StO_2). Newer-generation monitors that use near-infrared spectroscopy are reported to be unaffected by hypothermia and do not require the presence of a pulse.[3] Recent investigations using StO_2 monitors and their ability to discriminate between patients who require lifesaving interventions (LSIs)[4,5] and responsiveness to therapies[6] have been met with exuberance. Various threshold values of StO_2 have been correlated with resuscitation requirements and outcomes, including 1 study that found that StO_2 < 76% was an independent predictor of hospital admission from the emergency department[7] and another that found that StO_2 < 65% predicted the need for transfusion.[8] Using thenar StO_2 measurements in trauma patients admitted to an emergency department, StO_2 was found to be equally as accurate at predicting multiple organ failure as base deficit was for patients with severe blunt trauma to the abdomen.[3] An StO_2 value of less than 70% was associated with a sensitivity of 88%, specificity of 78%, and negative predictive value of 93% for identifying patients in need of a blood transfusion.[9] The use of StO_2 technology has the potential to obviate the need for more burdensome and invasive determinations of physiologic derangements such as prehospital lactate levels.[4]

This prospective observational study used a handheld near-infrared spectroscopy–based tissue oximeter to determine if a threshold value of StO_2 could help reliably detect patients in occult shock or in need of an LSI. We hypothesized that an StO2 value < 75% would be highly correlated with shock and the requirement for an LSI.

Methods

This prospective observational study was approved by The University of Maryland School of Medicine Institutional Review Board with a waiver of informed consent. Adult (>18 years of age) patients were enrolled if transported by 1 of 3 helicopter emergency medical services in the state of Maryland. The goal of this work was to identify a minimally invasive and easy-to-use handheld device that could identify patients in early-stage (compensated) hemorrhagic shock. A lightweight, handheld monitor without a need for calibration or additional provocative maneuvers is an unrealized yet highly desirable technology for both military and civilian prehospital providers. In this convenience sample, patients had to meet physiologic, mechanistic, or injury pattern criteria to be included, as listed in step 1, 2, or 3 of the Guidelines for Field Triage of Injured Patients.[10] Exclusion criteria were patients under the age of 18, patients with bilateral amputations that would preclude application of an oximeter to the thenar eminence, and patients who were pregnant or incarcerated. Data for those who were either dead on arrival or did not survive the first 30 minutes after arrival to the R Adams Cowley Shock Trauma Center at the University of Maryland were removed from the cohort. Patients were tested with 2 i-STAT (Abbott laboratories, Lake Bluff, IL) cartridges while in flight. The CG4+ measured lactate, pH, Pco_2, pO_2, total CO_2, total HCO_{3-}, base excess, and oxygen saturation, whereas the EC8+ cartridge measured hemoglobin, electrolytes, base excess, and glucose. Tissue oximetry was measured with an Inspectra 300 portable StO_2 monitor (Hutchinson Industries, Hutchinson, MN) attached to the thenar eminence. Although continuous data were generated, only 2 values were recorded: the first value obtained after takeoff and the last value on final approach to the trauma center.

Outcomes data were recorded to include resuscitation requirements at 1-, 3-, 6-, 12-, and 24-hour intervals. Resuscitation data comprised transfusion requirements including universal donor blood products or massive transfusions as defined by requiring greater that 6 units of packed cells within 6 hours or greater than 10 within 24 hours. LSIs included exploratory laparotomy, endotracheal intubation, tourniquet application, thoracostomy tube, and emergent resuscitative thoracotomy. Additional outcomes studied included survival to 48 hours, survival at discharge, intensive care unit length of stay, duration of ventilator requirement, and total hospital length of stay.

The primary goal of the analysis was to determine the correlation between the results of tissue oxygenation for identifying occult shock. Shock was defined by either a base deficit of >−4 or a lactate >3 mmol/L.[11-13] Secondary outcomes included the requirement for LSIs. Descriptive statistics were used to characterize the cohort. Data were compared using appropriate parametric and nonparametric tests for continuous variables and the Fisher or chi-square test for categoric variables. Areas under the receiver operating characteristic curve (AUROCs), plots that depict the true-positive rate versus the true-negative rate at various thresholds, were generated after a logistic regression model was selected and fitted. Independent variables (predictor variables) for the model included initial prehospital vital signs, the results of prehospital point-of-care testing, and StO_2.

After descriptive statistics were computed, Bayesian analysis was performed to assess the association with various covariates and outcomes of interest. A Bayesian approach was chosen for several reasons. First, previous information about the use of prehospital lactate, shock index, and other parameters were available.[4,14-17] Using existing knowledge, a posterior probability distribution can be calculated with the new data derived from this trial, thereby providing “updated knowledge.”[18] Previous information was incorporated into a model, helping mitigate the effect of a relatively small sample size.[19] Estimation precision in Bayesian models is not limited by sample size. Second, Bayesian inference provided a more intuitive interpretation of the results. Credible intervals (ie, the Bayesian equivalent of confidence intervals) can be calculated, which represent intervals to which parameters may be known with a certain probability. The ultimate goal of the Bayesian approach was to determine which variables added information (likelihood function) that could improve the ability to predict outcomes of interest (posterior probability) while incorporating known information based on previous studies (prior probability).

Multivariable logistic regression was performed to assess the ability of StO_2 to independently predict outcomes of interest. Outcomes of interest included the binary outcomes of survival and the need for LSIs. Once the regression model was selected and fitted, the outcome was regressed on all available covariates (predictors). All predictors with a *P* value >.20 were deleted, and the outcome was regressed on all remaining predictors. A process of variable deletion was repeated down to a *P* value of .05. The remaining predictors were evaluated with receiver operating curves, variance, net reclassification improvement, Bayesian information criteria, and integrated discrimination improvement. Predictors that did not contribute significantly to the model were omitted. The model was calibrated with the Hosmer-Lemeshow test and validated with resampling techniques (bootstrapping).

Statistics were performed using Stata Version 15.1 (StataCorp, College Station, TX), JASP Version 0.8.6 (JASP Team 2018, Amsterdam, Netherlands), and GraphPad Prism 7.0d (GraphPad Software, La Jolla, CA). A *P* value <.005 was considered statistically significant,[20,21] and all statistical tests using frequentist methods were 2-tailed.

Results

A total of 88 patients had StO_2 measurements in the field. Patient demographic and baseline characteristics are displayed in Table 1.

The median StO_2 value was 82% (interquartile range, 76%-87%; range, 42%-98%). The change in the initial and final StO_2 value was not statistically significant; a mean difference of <0.3% was observed with a standard deviation of 4% (Figure 1).

Eighteen patients (20%) had an abnormal StO_2 value (ie, StO_2 <75%). Eight patients were hypotensive before admission (9%), and 51% of patients had occult shock according to the laboratory parameters, but only 10 patients were correctly classified (9.5%) using an StO_2 <75% as a cutoff. Sensitivity and specificity using StO_2 to detect occult shock was poor (AUROC = 0.505; 95% CI, 0.47-0.53). Using a

Table 1
Demographics

Mean age (SD)	41.8 (17)
Minimum age	18
Maximum age	88
Sex (%)	
Male	69 (78)
Female	19 (22)
Median Charlson Comorbidity index (IQR)	0 (0-0.5)
Alcohol intoxication (%)	6 (6.8)
Injury type (%)	
Blunt	78 (88.6)
Penetrating	3 (3.4)
Isolated TBI	3 (3.4)
Blunt + penetrating	1 (1.1)
Other	3 (3.4)
Median Injury Severity score (IQR)	13 (5-25)
Median Revised Trauma Score in the field (IQR)	7.84 (7.55-7.84)
Median Revised Trauma Score on admission (IQR)	7.84 (7.55-7.84)
In-hospital mortality (%)	4 (4.6)
Types of patients (%)[a]	
Step 1	48 (54.6)
Step 2	30 (34.1)
Step 3	10 (11.4)

IQR = interquartile range; SD = standard deviation; TBI = traumatic brain injury.
[a] Classified per Centers for Disease Control and Prevention guidelines for field triage of injured patients.[10]

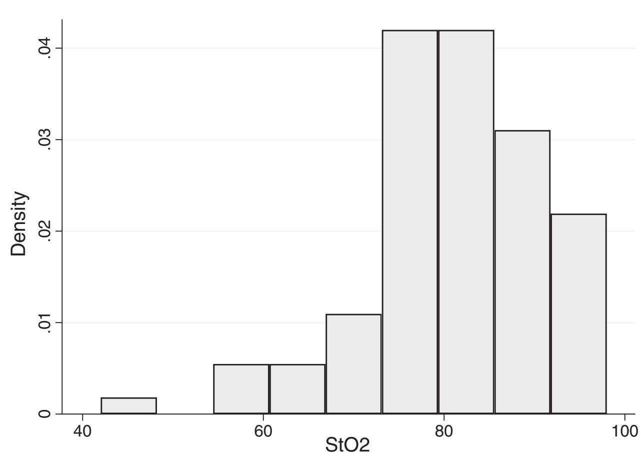

Figure 1. A histogram depicting the range of StO_2 levels.

Bayesian approach (Bayesian correlation), StO_2 correlated very poorly with laboratory-confirmed occult shock (Figure 2).

StO_2 did not correlate with prehospital lactate as evidenced by a very low Bayes factor (0.053) and a very low correlation coefficient ($r = -0.132$) (Figure 3). StO_2 values did not correlate with the requirement for LSIs as evidenced by a small Bayes factor (0.07; 95% credible interval, −0.002 to 0.17). Using a StO_2 threshold of <75%, sensitivity (6.2%), positive predictive value (27.8%), negative predictive value (68.6%) and overall accuracy (65.8%) were poor for the prediction of any prehospital LSI. Table 2 depicts the results of multivariable regression examining the need for an LSI as an outcome of interest.

Although statistically significant independent associations between increasing lactate and glucose and the need for an LSI were found, StO_2 was not associated with these outcomes. StO_2 was <75% in 1 patient who died; there was no statistically significant association between StO_2 level and death ($P = .86$).

Discussion

The goal of this study was to determine if a handheld tissue oximetry device could be used to detect early subclinical shock and to ascertain whether this information had utility for predicting the need for LSIs. Our results show suboptimal diagnostic and predictive capacity using a portable tissue oxygenation sensor. Tissue oximetry data did not contribute additional information regarding the detection of shock, mortality, or the need for LSIs when analyzed using state-of-the art statistical techniques.

Our work contrasts with previously published data that found strong associations between lower tissue oxygenation saturation values and the need for LSIs and the prediction of patient outcome.[4,5,7,9] The suboptimal sensitivity and specificity of the handheld oximeter used in our study may be attributed to a number of factors including different patient populations and different measurement techniques. Our technique, which involved simple application of the device to the thenar eminence as per manufacturer's instructions, was desirable for study from an operational standpoint because previously studied provocative maneuvers used in conjunction with tissue oximetry, such as the vascular occlusion test,[4] are not always feasible under battlefield conditions or when assessing multiple severely injured casualties. A major goal of this work was to determine the accuracy of a lightweight, portable, and easy-to-use device under conditions of duress, with a target provider population in prehospital military and austere environments where application of multiple sensors is not often not practicable.[22] The use of tissue oximetry in conjunction with additional maneuvers such as the vascular occlusion test have been reported to improve predictive capacity,[4] but these techniques are often difficult—and sometimes impossible—in high-paced prehospital settings including blackout operations in air medical environments, transportation of multiple casualties, and other austere settings.

Tissue oxygenation values did not correlate well with physiological measurements of occult shock such as base deficit and lactate levels, which have previously been shown to have strong correlations with outcomes and need of intervention.[11-13] This may partially be attributable to the rates of alcohol intoxication in this cohort and the effects of ethyl alcohol on laboratory values. Specifically, a potential for confounding exists because of the purported effect of alcohol on lactate levels, although significant elevations of lactate in patients with ethanol intoxication are rare in the absence of other causes of hemorrhagic shock.[27] Clearly, this was not the case in the study by Beekley et al[5] in which extremely low rates of alcohol use among the combat wounded could be safely assumed. The effect of alcohol on tissue perfusion is unknown, but it is possible that in acutely intoxicated patients known negative inotropic effects may have resulted in erroneous StO_2 and lactate measurements.[28] Perhaps most importantly, other studies selected patients for StO_2 monitoring who were already deemed to have evidence of shock with the goal of determining failure of response to interventions and progression to multiorgan failure as well as traditional methods.[3] Had our patient cohort been more critically ill, this StO_2 may have been more strongly associated with positive predictive values for the need for LSIs. Additionally, it is possible that our sample size was too small; this study represents a subgroup analysis for a larger study investigating the utility of point-of-care laboratory tests and continuous vital signs for the early detection of shock and prediction of LSIs. Only 88 patients could be enrolled before all devices became dysfunctional and could not be replaced under the funding stipulations.

In our study, higher than expected StO_2 results were observed for a majority of patients. These findings may be partly explained by the physiological phenomenon described by Fahraeus and Lndqvist.[24-26] The Fahraeus-Lindqvist effect describes how blood viscosity declines with smaller blood vessel diameters. This effect is a physiological response to vasoconstriction—an early response to hemorrhagic shock—whereby a core layer of red blood cells is assumed to be surrounded by an annular plasma layer.[25,26] In our study, all patients were rapidly exposed to an air medical system capable of rapid scene response and transport to a trauma center. With the exception of the

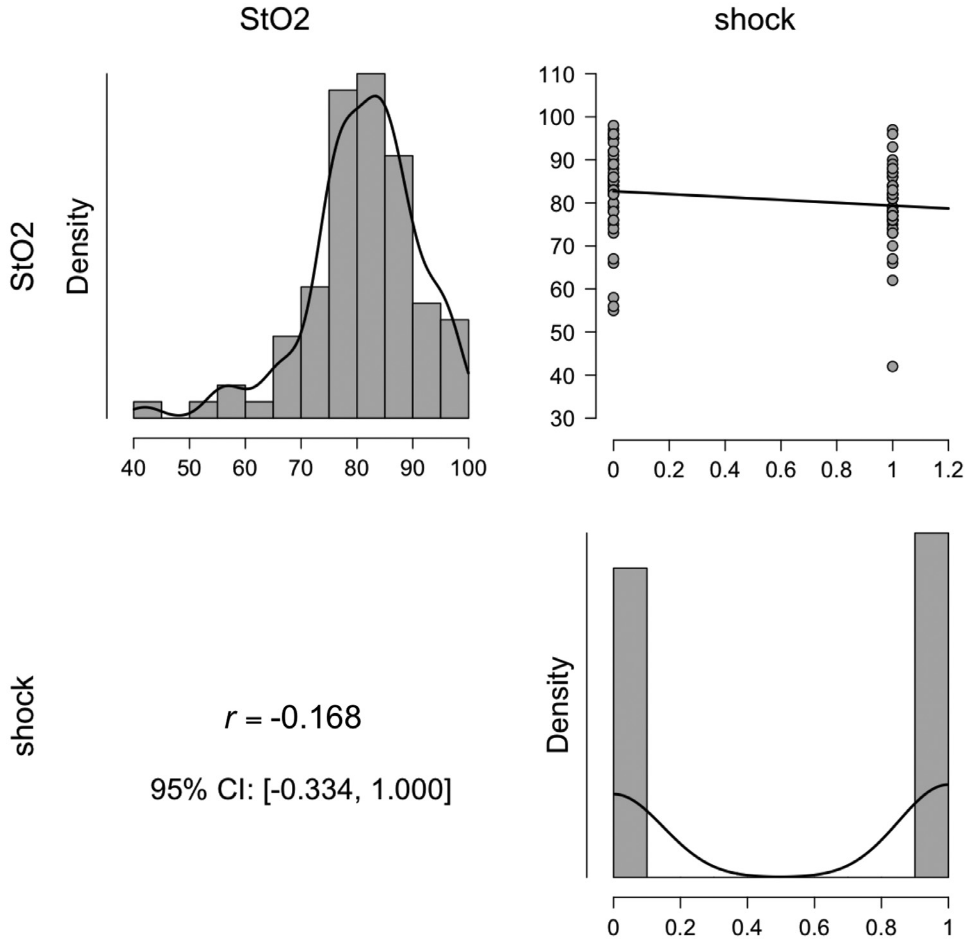

Figure 2. Bayesian statistics for the correlation of StO_2 and the presence of occult shock.

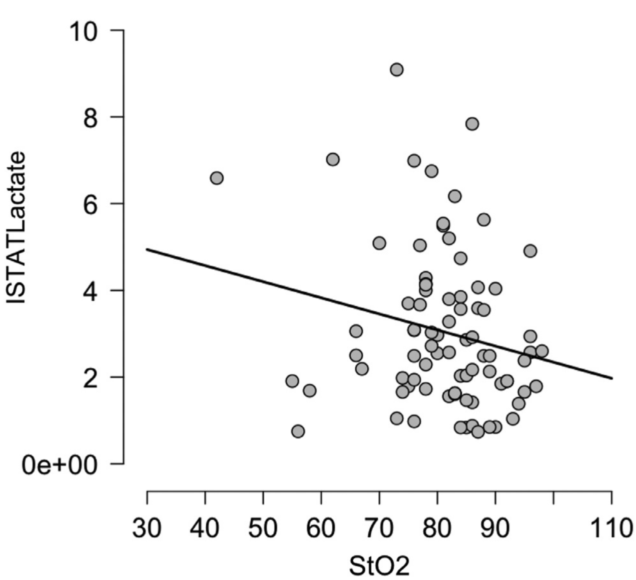

Figure 3. Bayesian correlation plot comparing StO_2 and prehospital lactate ($r = -0.132$).

most obviously and seriously injured patients enrolled in our study, the majority of seriously injured patients were likely in a state of compensated shock. Thus, because of the change in geometry of blood vessels, it is possible that asymmetric cell distribution resulted

Table 2
Logistic Regression Results With the Outcome of Interest Being the Need for a Lifesaving Intervention

Variable	Odds Ratio	95% Confidence Interval	*P* Value
Prehospital lactate level	1.91	1.26-2.9	.002
Prehospital glucose level	1.02	1.00-1.03	.043
Prehospital hemoglobin level	1.13	0.89-1.62	.51
StO_2	1.03	0.96-1.1	.46
Charlson index	0.94	0.46-1.91	.86
Male sex	2.19	0.35-13.74	.84
Age	0.97	0.92-1.03	.35

StO_2 = hemoglobin saturation in the capillaries, venules, and arterioles.

in a higher than expected StO_2 value because of changes in blood flow physics as a response to early hemorrhagic shock.[24] This phenomenon seems worthy of further study in future studies using next-generation tissue oximeters.

There are several additional limitations of this work. This study only measured 2 StO_2 values at distinct time points; had StO_2 been measured continuously, trends suggesting occult shock might have been evident. Sensor interfaces and limitations of the technology, including sensor attachments, may have also resulted in erroneous measurements. Finally, use in an air medical environment, albeit aboard a large, stable, low-altitude rotary wing platform, may have altered the results.

The determination of end-organ oxygenation is a desired parameter in trauma and critical care, both for triage purposes and to monitor for effectiveness of interventions. Although the use of tissue oximetry is included in the latest Joint Trauma System's clinical practice guidelines concerning damage control resuscitation,[23] tissue oximeters are not typically deployed among the United States' special operations teams. Indeed, in light of our findings, recommendations for the use of this technology should be critically reexamined. Although the results from this study cannot be used to endorse the use of the device tested, handheld tissue oximetry is an attractive technology that may have utility once refinements to the devices and techniques are made.

Supplementary materials

Supplementary material associated with this article can be found in the online version at https://doi.org/10.1016/j.amj.2019.03.014.

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