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Noninvasive Hemodynamic Monitoring In Emergency Trauma Patients

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Abstract

Noninvasive hemodynamic monitoring has evolved steadily over the past few decades in response to healthcare providers' preference for less invasive monitoring methods for their patients. Invasive monitoring has its place in the critically ill patient population as witnessed in intensive care units throughout the country. Even in this environment, providers are opting less for the pulmonary artery catheter which has been the gold standard for invasive cardiac output monitoring in the past. Providers are now utilizing less invasive monitoring techniques which offer fewer potential complications to the patient while providing rapid access to critically important hemodynamic data. Examination of different noninvasive hemodynamic monitoring systems was completed in a literature review. The findings indicate that clinical accuracy is variable from device to device, however as technology has progressed there has been general improvement in this area. The appropriate clinical use for noninvasive hemodynamic monitoring is discussed based on evidence from the literature with a focus on the benefits and drawbacks that are associated with these systems as they specifically apply to the emergent trauma patient population.

Introduction

Noninvasive monitoring technology is uniquely poised to be of great benefit to the emergent trauma patient population. Knowing these patients' hemodynamic status is critical to guiding management of these patients appropriately in the early stages of injury and resuscitation. Traditional monitoring of emergency trauma patients includes vital signs, urine output, and mental status. One of the problems with treating trauma patients solely by traditional measurements is that by the time there is a change noticed, the patient has decompensated towards a state of shock. As a patient's hemodynamic status worsens, their response to treatment also worsens, thus making correction of the injury increasingly difficult. Non-invasive monitoring techniques provide early recognition of changes in

hemodynamic status thus allowing for early treatment and improved responses to treatment. This pre-emptive treatment is critical for preventing hypoperfusion which can lead to irreversible organ damage, shock, and ultimately, death. Understanding the risks and benefits of noninvasive hemodynamic monitoring will help the nurse anesthetist to determine the appropriate application of these technologies towards improving the outcomes of their patients. This literature review examines the clinical research and application of various noninvasive hemodynamic techniques over the past 17 years. There have been multiple investigations of how noninvasive hemodynamic monitoring can be utilized in the hospital and emergency setting. The purpose of this literature review is to examine the evolution and application of specific noninvasive hemodynamic techniques as they apply to the trauma and emergency patient population.

Literature Review

Early noninvasive monitoring techniques were investigated by researcher Dr. William C. Shoemaker and his research colleagues. In 1999, they published a research article that examined the efficacy of early noninvasive hemodynamic monitoring after severe blunt trauma. They used a newly developed thoracic bioimpedance device which continually measured cardiac output and provided a continuous real-time display of data. The goal of the research was to determine if early identification and treatment of altered hemodynamic status via noninvasive monitoring in trauma patients would lead to more rapid and improved resuscitation (Velmahos, Wo, Demetriades, and Shoemaker, 1999). They noted that conventional monitoring which includes blood pressure, urine output, skin color, and mental status changes does not provide quantitative evaluation of cardiovascular function and these values may appear normal despite a significant hemodynamic deficit being present (Velmahos, Wo, Demetriades, and Shoemaker, 1999). The thoracic bioimpedance device was used in combination with a standard pulse oximeter, blood pressure cuff, a transcutaneous oxygen tension monitor, and a transcutaneous

carbon dioxide tension monitor. The authors utilized thermodilution from pulmonary artery catheters to compare cardiac output values measured by the noninvasive monitor. They found a correlation coefficient which the researchers determined to be acceptable in the clinical setting. "*The correlation coefficient for simultaneous pairs of samples of the two methods was r=0.91, r2=0.83. This is consistent with previous reports of critically ill patients predominantly in the ICU and was considered to be reasonably satisfactory from a clinical viewpoint*" (Velmahos, Wo, Demetriades, and Shoemaker, 1999). The research results indicated that survivors and non-survivors had significantly different values as measured by the noninvasive monitoring which included cardiac index, oxygen saturation, and percutaneous oxygen and carbon dioxide tensions. They argued that these values could be used in the early resuscitative period to guide treatment as adequate resuscitation in the initial period after traumatic injury is critical and may determine patient outcome (Velmahos, Wo, Demetriades, and Shoemaker, 1999). The authors concluded that the bioimpedance device correlated adequately with values measured simultaneously by pulmonary artery catheter thermodilution, however there was no clinically agreed level of acceptance from any other source that could confirm this adequate correlation between the two measurements; this was considered a limitation of the study (Velmahos, Wo, Demetriades, and Shoemaker, 1999). Identifying early altered hemodynamic status in emergency trauma patients via easy to use noninvasive monitoring was an important and clinically useful research topic that other researchers would continue to build upon.

Dr. Shoemaker was involved in another research project which utilized noninvasive monitoring as an early warning for the development of ARDS (acute respiratory distress syndrome) in trauma patients, published in 2000. The goal was to identify appropriate hemodynamic monitoring early after injury. Pulmonary artery catheterization, which is done in the critical care setting, provides metabolic oxygen delivery and consumption information, however this invasive monitoring is not readily available during the early resuscitation period in the emergency environment, whether that be the emergency

department or operating room (Tatevossian et al., 2000). The researchers continuously monitored patients with transcutaneous oxygen and carbon dioxide tension measurements which were considered a substitute for invasive blood gas monitoring which only provides spot checks as opposed to continuous trending information. Transcutaneous oxygen and carbon dioxide tensions were used to measure skin oxygenation and perfusion; the authors note that the skin is the first organ to manifest vasoconstriction and uneven blood flow from sympathetic stress stimulation thus providing a general picture of tissue perfusion function (Tatevossian et al., 2000). A thoracic electrical bioimpedance device was also used to monitor cardiac output noninvasively. The results of the study found certain trends that provided useful information; patients who did not develop ARDS had higher cardiac index and tissue perfusion levels than those who developed ARDS. The survivors of ARDS had higher cardiac output and tissue perfusion values than those who died after ARDS. This helped the authors to identify that monitoring and optimal treatment in the late stages after organ failure was ineffective due to severe oxygen debt already accumulated (Tatevossian et al., 2000). The authors found that early recognition of changes in tissue perfusion and cardiac output could guide pre-emptive treatment and decrease the risk that the patient develops ARDS with the application of these noninvasive monitoring techniques.

Shoemaker et al. (2006) published another article in the journal *Military Medicine* which examined how noninvasive monitoring for combat casualties could optimize patient outcomes. Shoemaker focused again on the importance of early monitoring and resuscitation in patients who had suffered traumatic injuries. Recognition of altered hemodynamic status is crucial in this initial period after traumatic injury. Delayed treatment has been shown to lead towards shock, organ failure, and death. The authors noted that goal directed resuscitation therapy with invasive pulmonary artery catheterization did not improve outcomes as this monitoring was usually started greater than 24 hours after hospital admission or after onset of organ failure; however early preoperative hemodynamic optimization showed significant improvement in patient outcomes (in the setting of peripheral vascular

surgery, trauma, cardiogenic shock, and sepsis) (Shoemaker et al., 2006). The researchers again used a thoracic bioimpedance device which was applied to patients shortly after arrival to the emergency department. They cited previous studies which documented satisfactory correlation between these noninvasive monitoring devices and the gold standard invasive pulmonary artery catheter thermodilution measurement of cardiac output. The authors did note the limitations of the bioimpedance device which is attached via thoracic electrode pads; these include faulty electrode placement, motion artifacts, patient restlessness, shivering, pulmonary edema, pleural effusion, valvular heart disease, dysrhythmias, and electrical leak from instruments using the same circuit (Shoemaker et al., 2006). The study included 851 patients who survived and 149 patients who died during hospitalization with the mortality rate at 14.9%. The authors generalized these large city trauma patients to similar combat casualties with the hypothesis that early noninvasive monitoring application on the battlefield would assist and guide first responders in their clinical judgment and treatment of these patients (Shoemaker et al., 2006). They found that the survivors of the study had mean values of cardiac index and mean arterial pressure that were significantly higher than those of the non-survivors thus reflecting the improved status of survivors' cardiac, pulmonary, and tissue perfusion functions (Shoemaker et al., 2006). The identification of these values early on as opposed to waiting for late signs such as hypotension and conventional signs of shock and hypoperfusion allows for early treatment and improved patient outcomes.

Dr. Shoemaker and his research team further examined the feasibility of noninvasive hemodynamic monitoring for early recognition and identification of circulatory problems in patients who had suffered thoracic and abdominal penetrating trauma injuries. The researchers again used a thoracic bioimpedance monitoring device (improved from previous models) which allowed for quick and easy application throughout the hospital environment (Asensio et al., 2006). They also compared their noninvasive monitoring values to pulmonary artery thermodilution values after Swan-Ganz pulmonary

artery catheters were placed postoperatively. The noninvasive cardiac output measurements were combined with pulse oximetry for estimation of arterial hemoglobin saturation which was meant to reflect pulmonary function; as well transcutaneous oxygen and carbon dioxide tensions which were utilized to reflect tissue perfusion and oxygenation. The authors found that the noninvasive systems provided essential clinical data early on that was previously unattainable without the presence of an invasive monitor such as a pulmonary artery catheter. Early circulatory abnormalities were identified in 91% of these severe trauma patients (Asensio et al., 2006). Regarding the correlation between noninvasive measurements and invasive measurements, the authors note that the differences in the absolute values of each simultaneous reading was offset by the value of continuous trending data being displayed by the noninvasive monitor (Asensio et al., 2006).

In yet another study directed towards examining the feasibility and reliability of multicomponent noninvasive hemodynamic monitoring for trauma patients in the emergency department and operating room, Dr. Shoemaker and his research team monitored 993 trauma patients with major blunt or penetrating injuries shortly after admission to the emergency department. Hemodynamic values were attained noninvasively by a thoracic bioimpedance device which was applied shortly after arrival of the patient to the ED (Shoemaker et al., 2006). The authors noted that application of the bioimpedance device simply entails applying leads, like an EKG, at the appropriate positions on the thorax. Invasive hemodynamic values were attained via pulmonary artery catheterization and a radial artery catheter (Shoemaker et al., 2006). The results demonstrated the limits of agreement between the invasive and noninvasive methods were 19.7% and the average difference between simultaneous noninvasive and invasive measurements was 9.7%. The authors concluded that this data demonstrated satisfactory agreement between the two methods, however the cost of noninvasive monitoring was only 11% of the cost associated with invasive pulmonary artery catheterization and monitoring (Shoemaker et al., 2006). The authors made an important observation

related to this research: in the early or incipient phase of trauma, shock frequently manifests as benign, however subsequently patients are found to deteriorate rapidly leading to critical illness, organ failure, and death (Shoemaker et al., 2006). The application of these noninvasive monitoring systems in the early phase of trauma and shock development can provide essential hemodynamic information to guide resuscitation before patients begin to deteriorate thus greatly improving their outcome. In addition, patients' response to treatment in this early stage is far greater than the response to treatment once they become critically ill.

There is a gap in some of the research on this topic after 2006, which may be due to limitations of noninvasive monitoring technology development. There were various noninvasive monitoring devices in development during this time. In 2010 a meta-analysis was published by the American Society of Anesthesiologists which examined the accuracy and precision of some minimally invasive monitoring devices which measured cardiac output during surgery and critical care. They examined 4 different monitoring methods including esophageal doppler, partial carbon dioxide rebreathing, thoracic bioimpedance, and pulse contour techniques (Peyton & Chong, 2010). The authors conducted a 10-year review of studies with the goal of examining the level of agreement between noninvasive methods and bolus thermodilution via pulmonary artery catheterization, the latter being considered the gold standard for comparison. Interestingly, these authors found that none of the four noninvasive methods met the criteria for acceptable agreement (determined in previous studies to be a percentage error of 30% or less) (Peyton & Chong, 2010). The weighted correlation coefficient was highest for thoracic electric bioimpedance at 0.79 and lowest with partial carbon dioxide rebreathing at 0.57. The authors recognized a significant number of limitations to their meta-analysis; of the 47 studies reviewed, 34 (72%) were done in cardiac surgery patients thus limiting the generalizability of the noninvasive devices beyond the cardiac patient to other patient populations. Cardiac patients may have heart dysrhythmias, valve disease, and other cardiovascular co-morbidities that limit the effectiveness of specific non-

invasive monitors (Peyton & Chong, 2010). Another limitation was the 10-year time span of their meta-analysis. Noninvasive monitoring was a rapidly developing field and they were unable to reflect improvements in newly available technologies. Findings did indicate the four monitoring methods achieved limits of agreement between each other that were acceptable and the authors note that this is significant as the methods utilize very different physical and physiological principles (Peyton & Chong, 2010). The absolute values derived from these noninvasive devices have been shown to be of less value than the trending information they provide. "In major surgery, reliable real-time tracking of the direction of changes in cardiac output is arguably more important than the ability of the monitor to deliver a highly accurate single measurement under stable conditions" (Peyton & Chong, 2010).

A study published in 2012 examined how a lightweight trauma monitor could provide early indication of central hypovolemia and tissue acidosis. The researchers used NIRS technology (near-infrared spectroscopy) to determine muscle hemoglobin oxygen saturation and muscle hydrogen ion concentration. This measurement of tissue pH is important as a clinical diagnostic value due to its significantly increased sensitivity to the development of shock as opposed to measures of arterial and venous pH (Soller et al., 2012). Noninvasive sensors were placed on the subject's forearms which collected reflectance spectra data from deep within the forearm muscle every 20 seconds. The researchers placed subjects in a lower body negative pressure environment to simulate a model of pre-shock hemorrhage. The results demonstrated that muscle oxygenation decreased in proportion to reductions in central blood volume with a strong positive relationship. The researchers also noted that muscle oxygenation was one of the earliest indicators of progressive central hypovolemia as compared with delayed alterations in standard vital signs. There was also a small yet significant reduction in muscle pH once muscle oxygenation levels reached a critically low level (Soller et al., 2012). The authors concluded that their research provided evidence that NIRS monitoring was capable of reflecting early signs of blood loss which can indicate that splanchnic organs may be experiencing inadequate oxygen

delivery (Soller et al., 2012). This noninvasive measurement of muscle oxygenation and pH were shown to be excellent indicators of early stage compensated shock. In addition, the NIRS monitoring system was designed to be lightweight, small, and easy to use (Soller et al., 2012).

The Nexfin noninvasive monitoring device, developed by Edwards Life Sciences, uses an inflatable finger cuff with a small box attached to the wrist which is used to indirectly measure finger arterial blood pressure. This value is then placed in an algorithm which converts the finger arterial pressure into beat-to-beat measurements of brachial blood pressures. In addition, the Nexfin device provides cardiac output values based on pulse contour analysis (Chen et al., 2012). This device was investigated in a study published in 2012 which assessed its ability to detect hypotension and hypertension earlier than the standard blood pressure cuff in patients undergoing general anesthesia. The sample included 25 patients referred for abdominal or orthopedic surgery. The researchers found that the median percentage error of the Nexfin cuff compared to the standard blood pressure cuff was 40.3% (Chen et al., 2012). The authors concluded that a concordance of only 81.3% between standard blood pressure readings and Nexfin readings necessitated further research to determine the accuracy of the Nexfin device (Chen et al., 2012). The real value of the Nexfin may be in observing trends of blood pressure which can assist in early detection of blood pressure changes and lead to timely intervention thus improving patient outcomes.

The NICOM (Noninvasive Cardiac Output Monitor) is another device based on thoracic bioimpedance technology which was developed by Cheetah Medical Inc. This device was utilized in a research study examining how noninvasive cardiac output measurements in the emergency department are associated with trauma activation, patient injury severity, and length of stay (Dunham et al., 2012). The NICOM sensors were applied to the torso after patients arrived to the emergency department at a Level I trauma center and monitoring was continued for 60 to 90 minutes. Cardiac output measurements were achieved easily and quickly once the sensors were in place. 270 patients were

included in the study with NICOM cardiac outputs available from 242, or 89.6%. The researchers found that the NICOM cardiac output values were significantly useful as they displayed appropriate variations with injury severity, co-morbidity, and survival in acutely injured trauma patients. The cardiac outputs were shown to be significantly higher in hypotensive patients who were not hemorrhaging as opposed to hypotensive patients that were hemorrhaging (Dunham et al., 2012). This was used to assist the clinician in choosing the appropriate treatment (I.e. fluids vs. vasopressors). Patient length of stay was shown to be increased in non-survivors (compared to non-survivors without NICOM who succumbed faster), but decreased in survivors (compared to survivors without NICOM that experienced increased complications requiring lengthier treatment) (Dunham et al., 2012). The NICOM device was found to be capable of providing objective, clinically valid, relevant, and discriminate cardiac output data in this adult acute trauma patient population (Dunham et al., 2012).

The Nexfin monitor was the subject of another research study published in 2013 which examined the validation of the device against continuous pulse contour and intermittent transpulmonary thermodilution via pulmonary artery catheter. Continuous pulse contour analysis was done via the PiCCO system (a less invasive system that requires a central line and arterial line, however still uses noninvasive pulse contour analysis to measure cardiac output) (Ameloot et al., 2013). The study included 47 critically ill patients admitted to the medical, surgical, and burn intensive care units at a major medical center. Results showed moderate to good correlation coefficients with the pulmonary artery catheter thermodilution method (0.68) and PiCCO method (0.71). The percentage errors were considered too high however to be considered clinically acceptable; the authors cited other research studies that came to similar conclusions when investigating the validity of the Nexfin device (Ameloot et al., 2013). The Nexfin device was found to be most accurate in patients with a high cardiac output and low systemic vascular resistance and least accurate in patients with the opposite characteristics such as in trauma and sepsis patients. Additionally, the Nexfin produced unreliable data in hypothermic

patients (Ameloot et al., 2013). The authors concluded that the Nexfin device may be an appropriate initial hemodynamic assessment that could act as a bridge to placement of more invasive/accurate monitoring systems. The value of the device may be found in tracking changes in cardiac output rather than relying on absolute values to determine cardiac output (Ameloot et al., 2013).

There was increased research on the various noninvasive hemodynamic monitoring systems as technologies continued to be modified and improved over time. The NICOM (Cheetah Medical) was investigated as being a feasible option for hemodynamic monitoring of air-evacuated casualties in a 2013 study. The study examined 16 patients who were air evacuated by the French army health service and placed on the NICOM monitor (Dubost et al., 2013). The researchers found that the monitor was feasible for transport during long flights without any signal loss or interferences noted and monitoring allowed for fine-tuning of fluid management in these unstable trauma patients (Dubost al., 2013).

Partial end-tidal carbon dioxide is another noninvasive monitoring method that has been utilized to determine cardiac output in patients. Dunham et al. (2013) investigated the statistical relationship between cardiac output and end-tidal carbon dioxide while at the same time correlating cardiac output levels with patient injury severity levels, blood pressure, heart rate, blood loss, transfusions, abnormal pupils, cardiac arrest, and death (Dunham et al., 2013). They reviewed 73 emergently intubated patient's records who had NICOM cardiac output monitors in place. They found that low end-tidal carbon dioxide levels were associated with low cardiac output and patients with major blood loss had a significant reduction in both of these values. Patients who were hypotensive but did not have blood loss displayed normal cardiac output and end-tidal levels implying that cardiac output and end-tidal carbon dioxide values may be helpful in making clinical decisions when managing hypotensive trauma patients (Dunham et al., 2013). The authors found that preserved cardiac output and end-tidal carbon dioxide levels in the hypotensive trauma patient implied the absence of blood loss. The authors do note that low levels do not necessarily indicate that there is hemorrhage as there can be

other causes of low cardiac output and end-tidal carbon dioxide (cardiac contusions, tamponade, tension pneumothorax, or heart failure) (Dunham et al., 2013).

Masimo is another company that has developed noninvasive hemodynamic monitoring devices; their Radical 7 system has been approved to measure hemoglobin noninvasively via a spectrophotometric self-calibrating sensor with light-emitting diodes and a photodetector which analyzes the patient via a finger probe (Moore, et al, 2013). Hemoglobin is commonly used to assist in identifying hemorrhage in trauma patients; trending these levels continuously would assist the clinician in identifying and treating blood loss. The system was investigated in a research study published in 2013 in order to evaluate the accuracy of the sensor hemoglobin levels to lab drawn hemoglobin levels. The patient sample was 525 trauma admissions for which 418 had readable outputs from the finger probe (Moore et al, 2013). The correlation between the sensor and lab drawn hemoglobin levels was found to be poor and in addition the device failed to detect hemoglobin values in 34% of the readouts. The authors note previous studies on this device have shown good clinical correlation in euvolemic patients; however accuracy was poor in patients with trauma and suspected blood loss (Moore et al., 2013). The Radical-7 was concluded to have limited clinical application in patients with hemorrhagic shock/trauma.

The Nexfin device was the subject of another study in 2014 which investigated whether the device could help diagnose patients suffering from suspected heart failure, sepsis, and stroke (Nowak et al., 2014). The researchers enrolled 514 subjects in the study with 4 excluded due to suspected finger cuff failure of the Nexfin unit. The data retrieved from the subjects showed that cardiac index and stroke volume index, as measured by the Nexfin, were highest in sepsis, followed by stroke, and lowest in acute heart failure (Nowak et al., 2014). The authors concluded that the data from the Nexfin could play a potential role in helping to diagnose and individualize treatment for this population of patients in the future (Nowak et al, 2014.)

The Nexfin has also been studied for its ability to measure pulse pressure variation and stroke volume variation for the monitoring of intraoperative fluid shifts. A 2014 research study observed 54 patient's response to a provoked fluid shift (patients were placed in Trendelenberg position). The Nexfin was able to reflect alterations in the pulse pressure variations and stroke volume variation while mean arterial pressure and cardiac index were not sensitive enough to reflect any changes (Stens et al, 2014). The Nexfin derived values of pulse pressure variation and stroke volume variation were of additional value to static indices for clinical assessment of fluid shifts in patients under anesthesia (Stens et al., 2014). The authors do note the limitation of the Nexfin's accuracy, "Nexfin cardiac values have proven to be unreliable in studies with critically ill patients, since they included patients with potentially compounding factors due to abnormal vascular tone, peripheral hypoperfusion due to septic shock, or cardiac stunning" (Stens et al., 2014). Trauma patients generally fall into the category of critically ill, which would limit the usefulness of the Nexfin device for this purpose.

The Radical-7 by Masimo was investigated in another research study designed to assess the accuracy of continuous noninvasive hemoglobin monitoring for the prediction of blood transfusion in trauma patients (Galvagno et al., 2014). The study enrolled 1191 patients of which 711 had available hemoglobin data obtained from the Radical-7 device. Subjects had the finger probe sensor applied upon admission to a trauma resuscitation unit with the primary outcome of interest being the administration of at least one unit of packed red blood cells within the first 12 hours (Galvango et al., 2014). Results showed that hemoglobin monitoring by the Radical-7 alone did not enhance predictive models showing the need for blood transfusion, however when combined with continuous vital signs, and adjusted for age and sex, the predictive value had good accuracy (Galvango et al., 2014). The researchers concluded that, in the trauma population, the cost of implementing such a device could not be justified until development of devices with increased accuracy (Galvango et al., 2014).

Joseph et al. (2015) examined the Radical-7 by Masimo, this time in the setting of trauma patients. The researcher's goal was to evaluate the efficacy and accuracy of a spot check noninvasive hemoglobin measuring device compared to invasive laboratory measurements in trauma patients (Joseph et al., 2015). The study sample included 525 patients with a successful readability rate of 86% thus reducing the sample to 450. They found that the difference between mean hemoglobin values of the noninvasive and invasive methods was only 0.3 g/do (plus or minus 3.6 g/do). The noninvasive spot check measurements were shown to have a strong correlation with the invasive measurements with 76% accuracy and 95.4 % accuracy (Joseph et al., 2015). The failure of the device to capture readings in 75 (14%) patients and the inconsistency of the device to collect measurements may be due to several factors such as low perfusion states, motion artifact, and disconnection of the sensor. In conclusion, the authors state that the inability of the device to recognize readings in trauma patients with life-threatening hemorrhage is a failure of the device and as a result, further evaluations need to be done before implementation of the device into clinical practice (Joseph et al., 2015).

The NICOM, a thoracic bioimpedance noninvasive cardiac output monitor, was the subject of investigation by researchers Berlin et al. in a study published in 2017 which was designed to test the researcher's hypothesis that the NICOM has acceptable agreement with bolus thermodilution from a pulmonary artery catheter in a wide range cardiac outputs. The researchers used a porcine model (8 Yorkshire swine weighing between 48-55 kg) of hemorrhagic shock and resuscitation as their model (Berlin et al., 2017). The data they collected and analyzed suggested an acceptable agreement between the invasive and noninvasive methods with a strong correlation between simultaneous measurements. The authors demonstrated a 97% concordance of values as plotted on a four-quadrant *x/y* axis. They made a distinction of cardiac output measurements that had also been made by other researchers: "Given the inherent error of all cardiac output monitoring (whether noninvasive or invasive), trending may be more important than the absolute values" (Berlin et al., 2016). The generalizability of the

porcine model to the human model is a limitation of the study although the authors claim this substitution is supported by previous use of porcine models to evaluate cardiac output monitors. The model used in this study claimed similar clinical features to human hemorrhage and resuscitation (Berlin et al., 2016).

A recent development in the field of noninvasive hemodynamic monitors is the Cipher Ox CRI (compensatory reserve index) tablet (tablet is their monitor platform, not an oral medication). The CRI is a new hemodynamic parameter which trends changes in a patient's intravascular volume relative to the individual patient's response to hypovolemia (Moulton et al., 2017). This index was just approved for use by the FDA in December of 2016. The CRI is a cardiovascular status indicator which is derived from a mathematical equation that equates the proportion of additional volume loss a patient can tolerate before hemodynamic decompensation occurs. CRI values range from 1 to 0 with 1 representing 100% and 0 representing 0%. The 1 corresponds to supine normovolemia while 0 implies imminent decompensation and circulatory collapse. The CRI decreases as a patient experiences volume loss, whether from bleeding or dehydration and CRI increases as the patient receives volume resuscitation. Patient tolerance to volume loss is different from individual to individual due to various factors such as ambient temperature, pain, medications, comorbidities, and innate physiologic capacity to compensate for volume loss (Moulton et al., 2017). The Cipher Ox tablet, which measures CRI via a finger probe, was evaluated in a research study that showed the CRI did have the ability to accurately, continuously, and noninvasively trend changes in intravascular volume for individual patients who experience moderate volume loss and replacement. Patients who had limited innate tolerance for volume loss had lower CRI estimates after blood loss than subjects who had a higher tolerance thus demonstrating the device's ability to individualize the CRI measurement effectively (Moulton et al., 2017). The clinical value of this device is observed as CRI values decrease over time which is indicative of rapid progression to hemodynamic decompensation due to central volume loss. The CRI has been shown to be far more

sensitive to volume loss than traditional monitoring methods when patients are asymptomatic (early phase of acute injury) and has also been shown to have increased accuracy in anticipating cardiovascular collapse when compared to derived parameters such as pulse pressure index and pulse pressure variation (Moulton et al., 2017). The limitation of this study is its application to trauma patients who have experienced major volume loss. The authors simulated blood loss by removing 333ml per subject rather than a percentage of blood loss per person. Other noninvasive hemodynamic monitoring systems that utilize finger sensor technology have proven to be accurate in normovolemic patients but inaccurate in patients that have undergone major volume loss (Moulton et al., 2017). The Cipher Ox tablet needs to be evaluated in the setting of the emergency trauma patient before introduction of this device into clinical practice with these types of patients.

In a recent study published in July of 2017, Masimo's Radical-7 probe was again evaluated for hemoglobin monitoring specifically in trauma patients. The subjects of this study were 113 trauma patients who already had hemoglobin levels less than 8gm/dL. Forty-three patients were excluded due to hemoglobin levels higher than 8gm/dL leaving 70 patients to be included in the study (Gamal et al., 2017). The researchers found low bias and strong correlation between noninvasive hemoglobin values and lab drawn values with a Pearson correlation coefficient of 0.872. The mean Radical-7 value for all samples was 6.7 gm/dL while the mean lab drawn value was 6.5 gm/dL (Gamal et al., 2017). Patients were measured at various stages in patient management including the resuscitation, preoperative, and intraoperative phases. The authors note that although all of their subjects were experiencing active bleeding, none of the subjects were in shock which may be an important limitation as the Masimo device has been shown to be more accurate in patients with adequate perfusion (Gamal et al., 2017). They conclude that the Radical-7 showed accurate precision in both absolute values and trend values compare to lab drawn measurements in trauma patients (Gamal et al, 2017).

The use of noninvasive hemodynamic monitoring in the clinical setting has been steadily increasing as evidence shows that hemodynamic instability and hypoperfusion are major contributing factors for organ failure and death. Invasive hemodynamic techniques have important limitations, especially towards treatment of trauma patients; this is evidenced by the time and personnel needed for pulmonary artery catheter placement. There are dangerous complications that can accompany this procedure as well such as central infection, blood vessel damage, severe bleeding, pneumothorax, damage to cardiac valve structures, and dangerous arrhythmias (Kuster, Exadaktylos, and Schnuriger, 2015). Noninvasive techniques offer a solution by allowing for easy, quick, and early application in the clinical and emergency setting during the initial evaluation of the patient. Noninvasive monitoring interferes less with clinical management than invasive methods and provides a continuous real-time display of measurements which permits early recognition of altered hemodynamic status compared to traditional monitoring methods in the early stages of trauma patient management (Kuster, Exadaktylos, and Schnuriger, 2015). The accuracy of various noninvasive techniques has been the subject of numerous research studies as seen in this literature review. Overall, the NICOM device has been shown to have the best accuracy in trauma patients with the Nexfin device providing the least accurate information, however each method has unique advantages and disadvantages which need to be acknowledged by the clinician. There is evidence pointing in different directions for the overall accuracy of specific devices. The research suggests that the best approach may be to utilize noninvasive monitoring as an adjunct to other patient information and data when making treatment decisions.

Discussion

The ability of the anesthesia provider to understand and effectively use these monitoring systems for their patients is essential. The value of these devices lies in providing early hemodynamic data that would otherwise only be attainable via placement of invasive monitors. Application of these

devices should be done by qualified pre-hospital emergency services or by emergency department providers once the patient has arrived at the hospital. This critical window of time in emergency trauma patients is invaluable at directing early resuscitation efforts and fluid replacement. Patients in the early stages of shock will not necessarily display changes in basic parameters such as vital signs, mental status, urine output, skin color, and temperature which makes early diagnosis and treatment of shock related to trauma extremely difficult. Early application of noninvasive hemodynamic monitoring can provide early warnings of impending shock and thus guide appropriate preemptive treatment which would assist in preventing the rapid deterioration that occurs in the later stages of shock. For those patients that require immediate life-saving surgery, the early resuscitation administered based on derived noninvasive hemodynamic data would greatly assist the anesthesia provider preparing to place the patient under anesthesia. These patients should have increased hemodynamic stability in the face of traumatic shock and the anesthesia provider will have a better idea of how their status is trending with regards to cardiac output and/or blood loss.

The NICOM device, a thoracic bioimpedance device which is applied with 4 leads on the thorax similar to ECG leads, has been shown to have the greatest accuracy for cardiac output compared to other devices although it has limitations as well. Funk, Moretti, and Tong (2009) explain that thoracic bioimpedance is affected by tissue fluid volume as well as volume changes of pulmonary and venous blood that are induced by respiration. As a result, this interference must be filtered out from the desired changes in volumetric blood flow of the aorta. Alterations in the position or contact of the electrodes will thus affect these measurements (Funk, Morreti, and Tong, 2009). Cardiac irregularities including dysrhythmias, valve disease, and right heart failure can also contribute to limiting the effectiveness of these devices. Newer devices have overcome some of these challenges by increasing signal processing as well as improving signal filtering, ECG triggering, arrhythmia detection, and respiratory filtering (Funk, Morreti, and Tong, 2009). Application of a thoracic bioimpedance monitoring

system would ideally be in the field or ambulance while on route to a level 1 trauma center, however placement in the emergency department would also be effective in identifying early changes in hemodynamic status. This monitor may become of less value once the patient is moved into the operating room and surgery commences as the intraoperative environment is less conducive to accurate measurements of cardiac output due to interference by noise from electrocautery, mechanical ventilation and surgical manipulation (Funk, Morreti, and Tong, 2009). The goal is for early resuscitation to be administered prior to the patient entering the operating room. In doing so, this will have prevented the patient from rapidly decompensating while additionally buying time for anesthesia personnel who are able to place more invasive lines once surgery has begun.

The noninvasive finger-cuff devices include the Nexfin device, which has been re-developed into the ClearSight system by Edwards Lifesciences. This technology utilizes a volume clamp method; this involves clamping the artery to a constant volume by dynamically providing equal pressure on either side of the arterial wall. The volume is measured by a photo-plethysmograph built into the cuff. The counter pressure is applied by an inflatable bladder inside the cuff and is adjusted 1000 times per second to keep the arterial volume constant. Edwards utilizes a mathematical real-time calculation referred to as Physiocal which determines the proper arterial 'unloaded' volume, i.e. the volume without a pressure gradient across the arterial wall. Per Edwards, the Physiocal method can analyze the curvature and sharpness of the plethysmogram during short episodes of constant pressure levels. Physiocal then automatically and periodically recalibrates the system to allow for accurate tracking of physiologic changes (Edwards Lifesciences, 2018). Like thoracic bioimpedance, this device can be applied in the pre-hospital setting by emergency services or in the emergency department and provide hemodynamic information including cardiac index, stroke volume, stroke volume variation, systemic vascular resistance and continuous blood pressure. One of the drawbacks associated with previous Nexfin technology has been the loss of accuracy in patients that are already hemodynamically

compromised and have low peripheral vascular resistance. Trauma patients are likely to fall into this category thus limiting the effectiveness of these devices in this patient population. Edwards reports improved accuracy with their most recent incarnation of Nexfin technology, the ClearSight system. One of the positive aspects of this device is that it can be brought into the OR with the patient and not suffer from interference caused by electrocautery. The device is also not likely to interfere with surgical prep or procedure as it stays on the patient's finger and wrist. Patient limiting factors that apply to this device include peripheral vascular disease, Raynaud's disease, or any other condition that affects circulation to the extremities.

The minimally invasive technologies that utilize pulse contour analysis were not included in the literature review as they require some invasive lines to function (usually an arterial line). These devices, which include the PiCCO, LiDCO, and FloTrac, are worth mentioning as they offer the same hemodynamic information provided by the noninvasive monitors however with improved accuracy as they are calibrated to an invasive line. These systems have drawbacks of their own though as pulse contour cardiac output measurements rely on a good quality of arterial trace; as a result, overdamping or underdamping can lead to unreliable cardiac output measurements (Critchley, 2011).

A noninvasive hemodynamic monitoring method that was not identified in the literature review is the esophageal doppler which utilizes ultrasound technology to measure cardiac output. The advantages of using Doppler technology include the ability to remain in position for days to weeks, its proximity to the aorta, and the size of the probe which is approximately the size of a nasogastric tube and can be positioned easily (Funk, Morreti, and Tong, 2009). Doppler technology relies on physiological assumptions such as the aorta being cylindrical shaped and predetermines the patient's aortic radius based on age, sex, weight, and height from which it calculates stroke volume based on pulsatile aortic blood flow (Funk, Morreti, and Tong, 2009). Esophageal doppler only measures descending aortic blood flow (70% of cardiac output), excluding blood flow to the aortic arch vessels, and as a result a correction

factor of 30%is introduced into the calculation of cardiac output. While this correction factor has been shown to be accurate in healthy individuals, the correction constant may not be suitable for patients in shock whose hemodynamic status may be undergoing drastic changes (Funk, Morreti, and Tong, 2009). Another limitation of this technology is that correct and accurate measurements are operator dependent and there is a relatively (compared to other noninvasive monitoring devices) steep learning curve. Probe position is critical to obtain accurate flow measurements and as a result additional training is necessary for staff to utilize this technology correctly. While esophageal doppler cardiac output measurements have been shown to have the highest accuracy when used correctly, this technology may not be ideal for trauma patients who are unstable as there may be spurious measurements recorded in the chaotic environment which usually surrounds an incoming trauma patient to the hospital. This technology may be of more use once the patient has been brought into the OR and anesthesia induction has commenced. Trans-esophageal echocardiogram ultrasound is a similar option for the patient in the operating room; this technology is also operator dependent as the provider must be trained to correctly perform a TEE to obtain accurate cardiac output values.

Masimo's noninvasive systems do not offer cardiac output measurements, however they do provide total hemoglobin, methemoglobin, carboxyhemoglobin, oxygen saturation, oxygen content, and pleth index from their Rainbow SET monitoring platform. The literature is variable on the accuracy of Masimo's devices. The most recent article on Masimo's noninvasive monitoring system published in 2017 shows a good correlation between lab drawn hemoglobin values and hemoglobin values derived from Masimo's finger probe. One of the issues that has been found to limit the accuracy of these devices (which was also a limitation with the Nexfin finger cuff technology) is patients who are in active decompensating shock. Studies have shown that the accuracy of these devices was reduced significantly in patients with severely compromised hemodynamic statuses. On the other hand, these devices are excellent for trending hemoglobin levels which may assist the provider in making the decision to

transfuse blood products. Literature suggests not relying solely on these devices to make a transfusion decision; its optimal use would be in assisting the provider to make a judgment in conjunction with other patient diagnostic information (vital signs, labs, urine output, surgical blood loss).

Each of these various noninvasive hemodynamic monitoring systems has been studied and used by clinicians with the goal of optimizing patient outcomes. The anesthesia provider who decides to utilize noninvasive monitoring for their patient needs to understand the appropriate application of these devices as well as the limitations that exist with each of these systems. The trauma patient would benefit most from noninvasive monitoring in the early stages of injury and shock where appropriate resuscitation would prevent acute decompensation. The patient's odds of a positive outcome following trauma surgery greatly increase if the acute decompensation of shock can be prevented or delayed. The provider should also recognize that the technology of these devices is always advancing. It is essential for the provider to continue to read the literature and studies on these devices as they progress and decide for themselves the appropriate use and value as pertains to their individual patient.

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