WHITE PAPER

A Paradigm Shift in Hemodynamic Monitoring: The Expanding Value of Venous Oximetry

INTRODUCTION

Once reserved for only the most critically ill patients, hemodynamic monitoring has evolved to play a significant role in the management of a wider range of patient populations.[1] Advanced technologies provide comprehensive data, including venous oxygen saturation, to guide proactive management of patients prior to hemodynamic crisis rather than reacting to late indicators of instability.

While venous oximetry, specifically central venous oximetry ($ScvO_2$), has most commonly been associated with Early Goal-Directed Therapy (EGDT) for the identification and treatment of severe sepsis and septic shock, it has also been clearly linked with improving outcomes in patients experiencing decreased cardiac output due to myocardial infarction, cardiac surgery, trauma or hemorrhagic shock, high-risk surgeries, and respiratory failure.[2,3,4,5,6,7]

This paper outlines the utility of venous oximetry for a variety of medical conditions as established through medical literature, clinical benefits and challenges of implementing it, and an overview of monitoring technologies that can be considered.

> Improvements in survival rates for acute myocardial infarction, trauma, stroke, and sepsis have been realized through early identification of tissue oxygen imbalance using hemodynamic monitoring combined with tissue perfusion therapy.

WHY MONITOR?

The purpose of hemodynamic monitoring is to ensure adequate tissue perfusion and oxygenation. This process occurs naturally in a healthy body as it responds to increased demand for oxygen or reduced arterial oxygen by increasing cardiac output to establish homeostasis. In the presence of critical illness or injury, however, the heart's ability to respond may be limited. As a result, depleted tissue draws oxygen from the venous oxygen reserve, leading to anaerobic metabolism and the production of lactic acid. If that is not addressed promptly, lactic acidosis and global tissue hypoxia ensues.

In recent years, improvements in survival rates for acute myocardial infarction, trauma, stroke, and sepsis have been realized through early identification of tissue oxygen imbalance using hemodynamic monitoring combined with tissue perfusion therapy. Additional evidence indicates that early initiation of hemodynamic resuscitation consistently improves mortality rates.[8]

WHAT TO MONITOR?

Continuous Measurement of SvO_2 & $ScvO_2$

The principles of oxygen transport and utilization are simple. Tissue consumes a percentage of delivered oxygen from blood for cellular respiration. The blood then returns to the venous circulation, where its oxygen content can be measured with a blood sample from the pulmonary artery or from the superior vena cava. Oxygenation measurements taken at the pulmonary artery are called mixed venous oxygen saturation, or SvO_2, while measurements taken at the superior vena cava are called central venous oxygen saturation, or $ScvO_2$. When a patient is unable to generate cardiac output sufficient to meet the metabolic needs of the tissue, the tissue extracts greater amounts of oxygen, leaving less oxygen present in the venous blood. This is reflected as a decreasing SvO_2 or $ScvO_2$ level. Conversely, when tissue does not extract the oxygen, both SvO_2 and $ScvO_2$ levels rise.

Various studies have shown that there can be slight differences between $ScvO_2$ and SvO_2 values—with either measurement reading 5-6% higher or lower than the other based on patient acuity.[9,10,11,12] However, the two have been shown to maintain a high correlation (see Figure 1).[9] As a result, $ScvO_2$ is accepted as an appropriate surrogate for SvO_2.

> In post-cardiac arrest patients, $ScvO_2$ may detect ongoing oxygen imbalances that do not fully resolve during resuscitation. $ScvO_2$ values below 40-50% indicate the likelihood of re-arrest, and $ScvO_2$ values above 60-70% indicate hemodynamic stability.[20]

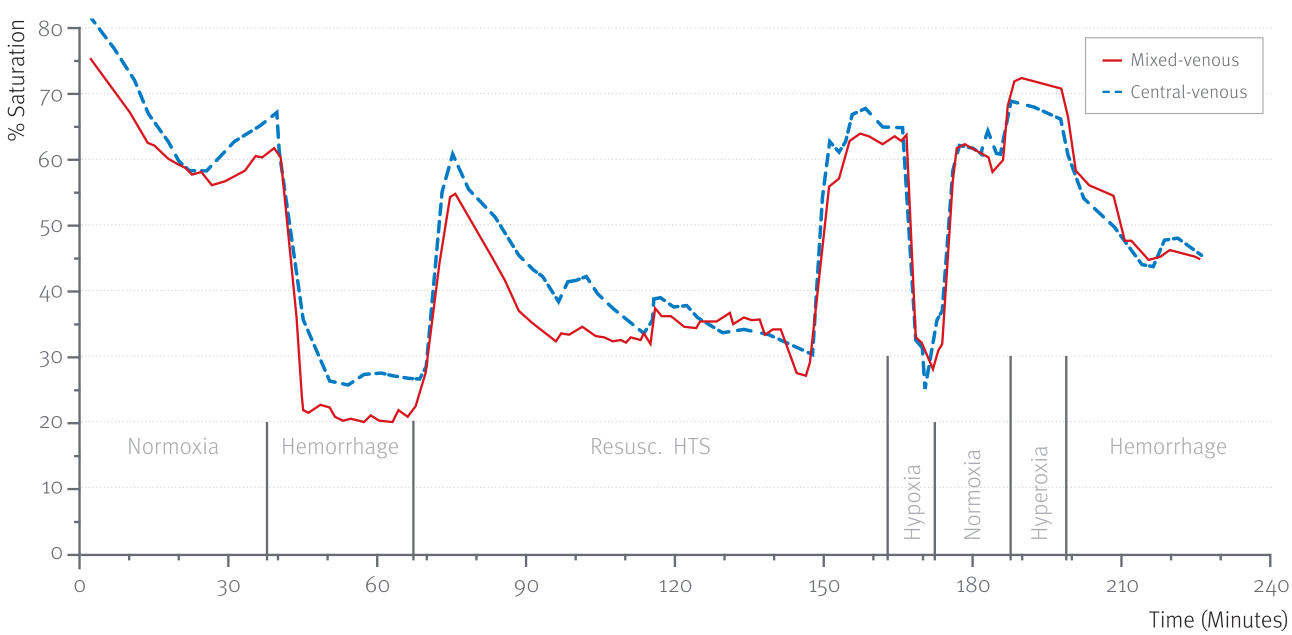
WHO BENEFITS?

Continuous venous oximetry can play a vital role in the effective management of critical care patients. Beyond identifying early signs of severe sepsis, $ScvO_2$ monitoring is an effective tool for diagnosing and managing patients during high-risk surgeries and conditions of myocardial infarction, cardiac failure, respiratory failure, and trauma (see Table 1).[2,3,4,5,13]

Sepsis

Sepsis is the condition most closely associated with use of continuous venous oximetry as part of EGDT protocols and the most studied to-date. In a study comparing continuous $ScvO_2$ monitoring with intermittent monitoring as a means to guide use of EGDT in sepsis, continuous monitoring had a greater success rate in achieving an ideal $ScvO_2$ target of 70% within six hours of diagnosis, resulting in quicker improvement of global tissue perfusion and improved survival.[14] Another study of continuous $ScvO_2$ monitoring in the treatment of sepsis found a 16% reduction in in-hospital mortality, a reduction in length of stay of approximately four days, and a savings of $12,000 per discharge.[15]

FIGURE 1. TIME COURSE OF MIXED AND CENTRAL VENOUS O_2 SATURATION DURING DIFFERENT EXPERIMENTAL PERTURBATIONS. HTS=HYPERTONIC SALINE SOLUTION (7.5%)[9]



A recent study evaluating EGDT using $ScvO_2$ has shown that the EGDT group and use of $ScvO_2$ resulted in outcomes comparable to usual-care in hospitals experienced in managing the septic population. Though the EGDT-managed group's total cost was higher when using a CVC oximetry catheter for $ScvO_2$, the authors of the study stated the cost difference was not significant.[16] Regardless, EGDT protocols have had an influential impact on clinical outcomes in the last decade, and the use of continuous venous oximetry monitoring is an important part of that protocol.[17]

In addition, patients at risk for severe sepsis often present with comorbidities where the availability of venous oximetry provides clinicians with invaluable physiological data with which to more effectively manage their patients.

TABLE 1. CLINICAL APPLICATIONS AND BENEFITS OF VENOUS OXIMETRY MONITORING (SvO_2 AND $ScvO_2$)[2,3,4,5,13]

PATIENT TYPE	
› Septic › Post-Coronary Artery Bypass Graft Surgery (CABG) › High-Risk Surgery	› Myocardial Infarction (MI) › Trauma › Respiratory Failure

BENEFIT OF MONITORING	
› Indication of adequate cardiac output (CO) › Decreased length of stay (LOS) › Decreased morbidity/ mortality	› Indication of O_2 consumption › Indication of additional interventional needs › Improved outcomes

Cardiac Care

Nearly five million Americans live with congestive heart failure (CHF), resulting in roughly 875,000 hospitalizations each year where the primary diagnosis is CHF.[18] Although cardiac patients are at high risk for developing global tissue hypoxia, vital signs and findings from physical examination have been the primary diagnostic tools guiding emergent care. Research supporting the use of hemodynamic monitoring via $ScvO_2$ in this patient population is growing. The use of continuous $ScvO_2$ monitoring, coupled with lactic acid measurement, has been shown to be superior to the assessment of vital signs alone for identifying tissue hypoxia in cases of cardiogenic shock and for guiding the implementation of early, aggressive management strategies (see Table 1).[3]

Several studies have also shown the usefulness of $ScvO_2$ monitoring for patients in acute cardiac arrest.[6,19] One study reported that with an $ScvO_2$ level greater than 60%, return of spontaneous circulation was likely to occur, while an $ScvO_2$ value greater than 72% was associated with a certain return of spontaneous circulation.[3] Additional research suggests that in post-cardiac arrest patients, $ScvO_2$ may detect ongoing oxygen imbalances that do not fully resolve during resuscitation. Specifically, an $ScvO_2$ value below 40-50% indicates the likelihood of re-arrest, and an $ScvO_2$ value above 60-70% indicates that the patient is hemodynamically stable.[20]

> For patients with trauma and hemorrhagic shock, an $ScvO_2$ value less than 65% measured in the first 24 hours after admission is associated with higher mortality and prolonged ICU and hospital length of stay.[29]

Roughly 10% of cardiac patients require prolonged postoperative care because of hemodynamic instability, organ dysfunction, or multiple organ failure—and this patient population is likely to grow as surgical and technological advances enable surgery on traditionally high-risk patients.[21] In the immediate post-cardiopulmonary bypass period, inadequate oxygen delivery is a known predictor of a prolonged ICU stay, while the recognition of improved cardiac output and subsequent enhancement of oxygen consumption are clearly associated with improved outcomes.[22,23] The information gleaned from $ScvO_2$ monitoring also helps to guide the delivery of intravenous fluid and vasopressor/inotropic therapy for these cardiac patients.[24]

Trauma

Traumatic injury may result in tissue hypoxia, oxidative stress, capillary leakage, and metabolic changes.[25] More importantly, tissue hypoxia within the first 24 hours after a traumatic event has been shown to be a predictor of multiple organ dysfunction syndrome.[26] Yet, as with many other critical care situations, the assessment of vital signs remains the gold standard used to detect and treat shock states in trauma patients, when in fact, $ScvO_2$ monitoring has demonstrated significant advantages over vital signs assessment.

For patients with trauma and hemorrhagic shock, an $ScvO_2$ value less than 65% may indicate that additional resuscitation or surgical intervention is needed.[27,28] In addition, an $ScvO_2$ value less than 65% measured in the first 24 hours after admission is associated with higher mortality and prolonged ICU and hospital length of stay.[29] $ScvO_2$ measurement was also shown to be a trustworthy parameter to estimate blood loss, especially in patients with an $ScvO_2$ level below 65% despite stable vital signs.[4]

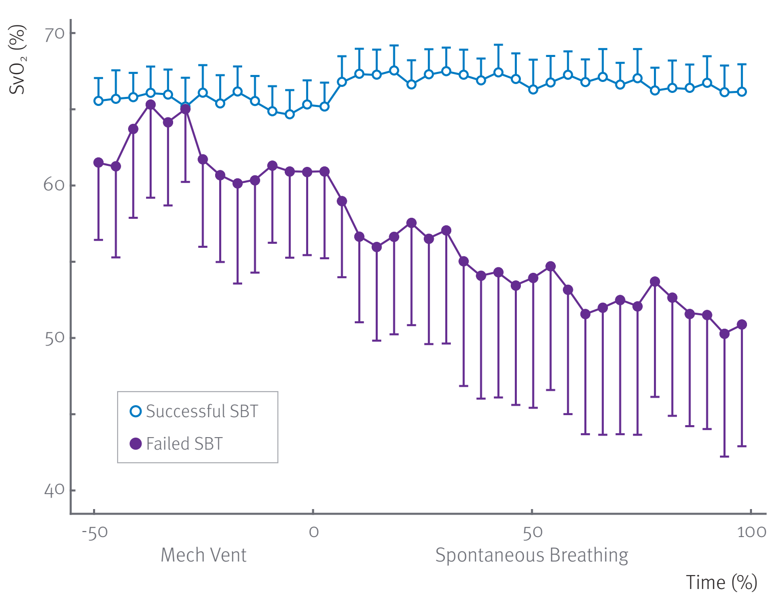
This lack of linear correlation between low $ScvO_2$ and stable vital signs has been corroborated by a non-randomized study of patients presenting to the emergency department in shock conditions who presented an $ScvO_2$ value below 65% in almost half of cases, despite other hemodynamic parameters appearing stable.[5] Conversely, patients with $ScvO_2$ values greater than 65% discharged alive from the ICU had significantly shorter ICU and total hospital lengths of stays.[29]

High-Risk Surgery

Surgical patients are subject to the effects of anesthesia, surgical trauma, inflammation, fluid shifts, and blood loss. In extensive surgical procedures these effects are magnified, which may impair oxygen delivery to organs and tissues, triggering organ failure. The development of postoperative organ failure in 27-77% of high-risk surgeries, such as organ transplants, severely effects the prognosis of patients and substantially increases the utilization of resources and cost of care.[30] Length of stay and postoperative mortality are also increased in these high-risk patients.[7,31] Consequently, the use of early and efficient means to detect and treat potential triggers of organ failures, such as tissue hypoxia, is particularly important in this population.

In a study that used $ScvO_2$ and arterial lactate as two indices of tissue level oxygenation, lactate consistently rose later than $ScvO_2$.[30] Interestingly, organ failures were observed much more often in patients with at least one elevated lactate value. Thus, the researchers concluded that staving off organ failure is reliant on earlier and more aggressive hemodynamic management before lactic acidosis commences.

FIGURE 2. VALUES OF SvO_2 DURING MECHANICAL VENTILATION AND A TRIAL OF SPONTANEOUS BREATHING IN THE SUCCESS GROUP[38]

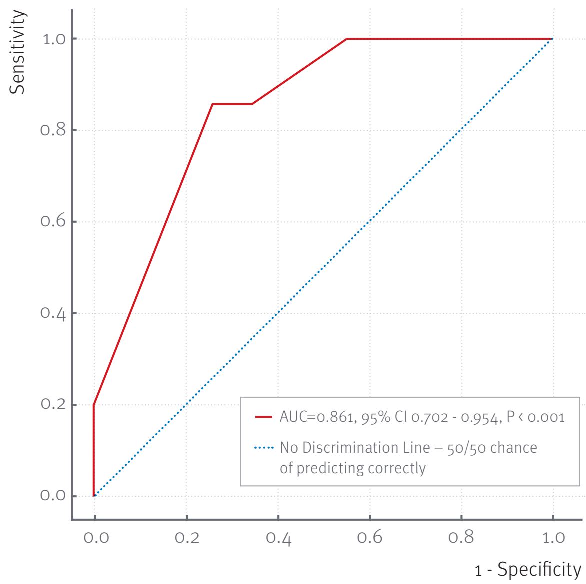


The rapid decrease of SvO_2 at the onset of the spontaneous breathing trial is highly predictive of unsuccessful weaning.

Respiratory failure

There are as many as 200,000 cases of acute respiratory distress syndrome (ARDS) and acute lung injury (ALI) reported in the U.S. each year.[32] Due to the increased risk of complications, the use of pulmonary arterial catheterization for routine monitoring of these patients is not recommended.[33] However, the World Health Organization advises healthcare providers to "closely monitor patients with severe acute respiratory infections for signs of clinical deterioration, such as severe respiratory distress/respiratory failure or tissue hypoperfusion/shock, and apply supportive care interventions."[34] In the early phase of ARDS, an associated septic state is usually responsible for fluid retention, and hemodynamic optimization is critical to stabilizing the patient.[35] Therefore, $ScvO_2$ is especially important in managing this complicated patient population.

FIGURE 3. ROC CURVE OF Δ $ScvO_2$ IN PREDICTING EXTUBATION FAILURE (AUC=0.861, 95% CI 0.702 - 0.954, P < 0.001)[41]



The AUC=0.861 shows that Δ $ScvO_2$ has a very good discriminative predictability for when a patient will fail to extubate.

ARDS patients require longer periods of mechanical ventilation which are associated with longer ICU stays.[36] Weaning ARDS patients from the ventilator can be a difficult and prolonged process. Generally, tolerance of a spontaneous breathing test (SBT) indicates weaning success, but less effectively predicts extubation success. In fact, the need for reintubation within 24 to 72 hours occurs in 5-30% of patients, dependent on the population.[37] Research shows that patients who failed weaning also failed to increase oxygen delivery to tissues (see Figure 2).[38] This respiratory exhaustion, a common challenge post-extubation, is reflected in near real-time through $ScvO_2$ measurement. As such, in the weaning process, measurement of $ScvO_2$ has the potential to be a reliable and convenient tool to rapidly warn of acute changes in the oxygen supply and demand of these patients.[39] In separate studies, researchers reported that a reduction in $ScvO_2$ by ≥4.5% during the SBT was an independent predictor of reintubation.[40]

Another study showed the difference between $ScvO_2$ at the 1st and 30th minute of a spontaneous breathing trial as a predictor of extubation failure. Their multivariate regression identified this difference (Δ $ScvO_2$) as the only independent variable able to discriminate extubation outcomes. The receiver operating characteristics curve yielded an area under the curve (AUC) of 0.861 (see Figure 3).[41]

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VENOUS OXIMETRY MONITORING TECHNOLOGIES

Pulmonary Arterial Catheters (PAC)

SvO_2 is not readily measurable without a pulmonary artery catheter, a technology that has created enthusiasm as well as controversy in its 40-year history. Apart from its pressure and SvO_2 monitoring capabilities, pulmonary arterial catheterization can measure cardiac output using a method called thermodilution. Cardiac output measurements from PACs are then combined with other hemodynamic measurements to calculate systemic and pulmonary vascular resistance. Use of PACs does not come without risk of complications, including pneumothorax, hemorrhage, pulmonary artery rupture, and pulmonary embolism,[42] leading some clinicians to question their value.[43]

Central Venous Oximetry Catheters (CVOC)

$ScvO_2$ measurements are traditionally obtained by a CVC with fiber optic oximetry, as opposed to a more invasive PAC. Placement of a CVC is easier to perform and has fewer inherent risks than placement of a PAC, allowing $ScvO_2$ monitoring to benefit patients and clinicians in a variety of settings where insertion of a PAC is not feasible.[11]

There has been considerable discussion regarding $ScvO_2$ as a substitute for SvO_2, and an extensive bibliography supports its use in hemodynamic monitoring.[44,45] At the center of this research, a prospective cohort study found the venous-arterial oxygenation differences obtained from the pulmonary artery and central venous circulations were equal and inversely correlated with the cardiac index.[45]

Another study showed that an $ScvO_2$ value may be used as a surrogate marker to reflect adequacy or inadequacy of cardiac output.[46] Studies suggest $ScvO_2$ may show that a lower cardiac output or mean arterial pressure (MAP) is sufficient to meet the current metabolic demands of the patient, reducing reliance on pressors, oxygen/mechanical ventilation, blood products and/or inotropes.[47, 48]

> Utilizing a PICC line for venous oximetry would allow for less invasive and more cost-effective $ScvO_2$ monitoring without the infection potential associated with a direct neck puncture.

While less invasive than PAC placement, the use of CVCs is also not without risk. Complications of CVC insertion may include pneumothorax, hematoma, carotid artery puncture, and infection. Additionally, because a CVC is intended for a short period of use, repeated insertions are necessary when long-term monitoring is required, impacting patient comfort and increasing the risk of infection while potentially limiting future vascular access.

Less Invasive Venous Oximetry

Peripherally inserted central venous catheters (PICCs) have been safely used for many years to access the central venous circulation to administer fluids such as parenteral nutrition, chemotherapy, vasopressor, antibiotics and other solutions, and facilitate blood draws. More than one million PICCs are placed each year in the U.S. alone.[49] Because of this ability to access the central venous circulation at the superior vena cava, PICCs are a less invasive avenue to consider for venous oximetry.

Currently, the only available PICC line with oximetry monitoring technology is the TriOx®–PICC minimally invasive oximetry sensor (ICU Medical Inc., San Clemente CA). TriOx-PICC uses three-wavelength oximetry technology to filter noise and artifact caused by cell orientation, vessel wall reflections, and changes in pH.

The use of a PICC has several significant advantages over the use of CVCs. PICCs avoid the complications associated with the direct neck puncture of the central venous circulation system.[50,51,52] These devices have also been shown to have lower catheter-related bloodstream infection (CRBSI) rates as compared to CVCs[53] and support a longer period of use.[54]

Because PICC lines can be inserted by trained nurses outside the operating room, PICC use reduces cost and decreases treatment delays common in busy operating or intensive care units.[55] So in addition to being less invasive and potentially safer, PICCs are also a more convenient, efficient, and cost-effective method to access $ScvO_2$ levels.

CONCLUSION

Venous oximetry has been established as a valuable method to monitor and maintain adequate tissue oxygenation and avoid hemodynamic crisis in critically ill and at-risk patients. $ScvO_2$ has been shown to be a surrogate measurement for SvO_2, reducing the reliance on invasive pulmonary artery catheterization. Its broad utility has been demonstrated across a variety of conditions, from cardiac care to trauma, respiratory failure and high-risk surgery, in addition to its origins in the treatment of sepsis.

The TriOx-PICC minimally invasive oximetry sensor (ICU Medical, Inc., San Clemente CA) allows clinicians to monitor continuous $ScvO_2$ less invasively and more cost-effectively than with traditional central lines.

The technology used to obtain venous oximetry measurements has evolved from pulmonary artery catheterization to less invasive central venous catheterization, with the goal of increasing patient safety, reducing costs, and minimizing procedure time. As the industry continues to migrate toward less invasive and more cost-effective patient monitoring trends, PICC line oximetry will continue to become a viable and efficient method for monitoring $ScvO_2$.

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