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NARRATIVE REVIEW

Hemodynamic monitoring with two blood gases: "a tool that does not go out of style"

Monitoreo hemodinámico con dos gasometrías: "Una herramienta que no pasa de moda"

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Abstract

Hemodynamic monitoring of a critically ill patient is an indispensable tool both inside and outside intensive care; we currently have invasive, minimally invasive and non-invasive devices; however, no device has been shown to have a positive impact on the patient's evolution; arterial and venous blood gases provide information on the patient's actual microcirculatory and metabolic status and may be a hemodynamic monitoring tool. We aimed to carry out a non-systematic review of the literature of hemodynamic monitoring carried out through the variables obtained in arterial and venous blood gases. A non-systematic review of the literature was performed in the PubMed, OvidSP and ScienceDirect databases with selection of articles from 2000 to 2019. It was found that there are variables obtained in arterial and venous blood gases such as central venous oxygen saturation ($SvcO_2$), venous-to-arterial carbon dioxide pressure ($\Delta pv\text{-}aCO_2$), venous-to-arterial carbon dioxide pressure/arteriovenous oxygen content difference ($\Delta pv\text{-}aCO_2/\Delta Ca\text{-}vO_2$) that are related to cellular oxygenation, cardiac output (CO), microcirculatory veno-arterial flow and anaerobic metabolism and allow to assess tissue perfusion status. In conclusion, the variables obtained by arterial and venous blood gases allow for non-invasive, accessible and affordable hemodynamic monitoring that can guide medical decision-making in critically ill patients.

Key words

Hemodynamic monitoring; blood gas; cardiac output; carbon dioxide; microcirculation.

Resumen

El monitoreo hemodinámico de un paciente en estado crítico es una herramienta indispensable tanto dentro como fuera de la terapia intensiva; actualmente se cuenta con dispositivos invasivos, mínimamente invasivos y no invasivos; sin embargo, ningún dispositivo ha demostrado tener impacto positivo en la evolución del paciente; la gasometría arterial y venosa proporcionan información del estado microcirculatorio y metabólico real del paciente pudiendo ser una herramienta de monitoreo hemodinámico. El objetivo de esta revisión fue realizar una revisión no sistemática de la literatura del monitoreo hemodinámico realizado mediante las variables obtenidas en la gasometría arterial y venosa. Se estudiaron las bases de datos de PubMed, OvidSP y ScienceDirect con selección de artículos del 2000 al 2019. Se encontró que hay variables obtenidas en la gasometría arterial y venosa como la saturación venosa central de oxígeno ($SvcO_2$), la diferencia de presión venoarterial de dióxido de carbono ($\Delta pv\text{-}aCO_2$), la diferencia de presión venoarterial de dióxido de carbono/diferencia del contenido arteriovenoso de oxígeno ($\Delta pv\text{-}aCO_2/\Delta Ca\text{-}vO_2$) que están relacionadas con la oxigenación celular, con el gasto cardiaco (GC), con el flujo venoarterial microcirculatorio y con el metabolismo anaerobio que permiten realizar una valoración del estado de perfusión tisular. En conclusión, las variables obtenidas por gasometría arterial y venosa permiten realizar un monitoreo hemodinámico no invasivo, accesible y asequible que pueden guiar la toma de decisiones médicas en el paciente en estado crítico.

Palabras clave

Monitoreo hemodinámico; gasometría; gasto cardiaco; dióxido de carbono; microcirculación.

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INTRODUCTION

Monitoring, whether it be invasive, minimally invasive or non-invasive, supports clinical decision-making, hence its preeminent role in critical care. However, sufficient evidence on improved outcome data using one or another form of monitoring is still lacking (1). The most important thing will always be monere: warn or alert to prompt a decision before an event happens. The majority of the variables involved in hemodynamic monitoring hint at macrocirculation, because it appears to make sense that addressing macrohemodynamic variables should improve microcirculation (hemodynamic coherence); however, oftentimes this does not happen (2). Various techniques, methods and devices, ranging from clinical to invasive monitoring, are available to assess microcirculation abnormalities (3). In fact, across time, blood gases continue to prevail over lactate, base deficit (BD) or central venous oxygen saturation (ScvO2), because we know today that venous-to-arterial carbon dioxide pressure difference (Δpv-aCO2) or venous-to-arterial carbon dioxide pressure/arteriovenous oxygen content difference (Δpv-aCO2/ΔCa-vO2) reflect to cardiac output (CO), microcirculatory blood flow and anaerobic metabolism, which is perhaps the true target (4,5).

Clinical findings in shock are sensitive but not very specific when it comes to assessing microcirculatory blood flow, and practically of no account when it comes to anaerobic metabolism. Information provided by blood gases is a closer reflection of the true microcirculatory and metabolic status of the patient, as they show dysoxia and hemodynamic incoherence (6,7).

OBJECTIVE

To conduct a non-systematic review of the literature on hemodynamic monitoring using variables derived from arterial and venous blood gases.

METHOD

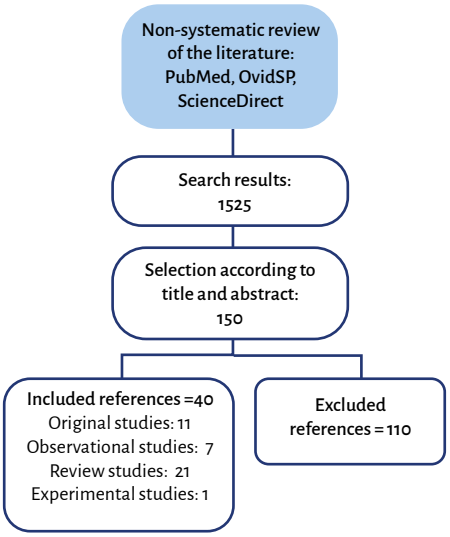
Non-systematic review of articles published between 2000 and 2020 in PubMed, OvidSP and ScienceDirect databases, using the following search terms in Spanish and English: hemodynamic monitoring, microcirculation, central venous oxygen saturation, venous-to-arterial carbon dioxide difference, venous-to-arterial carbon dioxide difference over arteriovenous oxygen content delta. Articles were selected according to title and abstract, and observational, review and original articles were included, while those that did not provide relevant information for the objective or were outside search dates were excluded. The results of this review were consistent with the authors' perspective regarding relevance, and were included if at least four authors were in agreement (Figure 1).

DEVELOPMENT

Central venous oxygen saturation (ScvO2)

A central venous catheter (CVC) and an arterial line (AL) are part of the devices required for patients in an intensive care unit (ICU) and samples from each of those lines can provide crucial information (8). The monitor is enough to gain insight into the macrocirculatory status but, for microcirculation, central venous and arterial blood gases are an excellent choice.

FIGURE 1. Flow diagram of reference search and selection.



SOURCE: Authors.

In healthy individuals, ScvO2 is lower than mixed venous oxygen saturation (SvmO2) by approximately 3%. This is explained by lower oxygen extraction (O2ER) from the lower body as compared to the upper body. However, this ScvO2 /SvmO2 ratio is inverted in shock. In patients with septic shock, ScvO2 is greater than SvmO2 by up to 8%, as a result of increased O2ER from the lower body (gastrointestinal tract) (9). Some studies have shown that ScvO2 may be an excellent proxy for SvmO2 values. In pathological conditions, ScvO2 rises or falls, with 70% being the normal or reference value (10).

ScvO2 is a VO2/DO2 (oxygen consumption/oxygen delivery) dependent variable: it drops when oxygen transport is low (high VO2/DO2) and increases when oxygen usage is low (low VO2/DO2). When DO2 drops, compensation occurs through O2ER increase but, without the right intervention, the compensation mechanism is not sufficient, the target point being VO2 dependence on DO2. Up to that point (cell dysoxia) ScvO2 drops in tandem with DO2 reduction and, from then on, anaerobic metabolism may give rise to disproportionate changes due to tissue hypoxia secondary to delays in timely and adequate interventions. Consequently, ScvO2 reliably reflects cell oxygenation status. In the context of low ScvO2, DO2 increase (in dependent zone) involves an increase in VO2 and, despite adequate intervention, ScvO2 remains low and will increase only after VO2 is no longer dependent on DO2 (independent zone). Low ScvO2 is not equal to DO2 increase (fluids, inotropes, vasopressors, beta-blockers, transfusion, oxygen) because such an intervention may have undesirable consequences. Rather, the answer is to reduce VO2 (pain control, sedation, mechanical ventilation, fever control, treatment for agitation, tremor or shivering control) and, consequently, perhaps the best option is a personalized intervention. High ScvO2 may be an indication of impro-

vement, but also of inadequate VO2. Therefore, elevated SvcO2 does not rule out the need for therapeutic interventions and, in any case, whether it is low, normal or high, the best option is to add Δpv-aCO2 and Δpv-aCO2/ΔCa-vO2. Although lactate can be used, it is not the best option because it does not necessarily reflect tissue hypoxia or anaerobic metabolism; it should not be interpreted as a single or isolated variable, considering that there are non-hypoxic mechanisms that determine a higher reading (11,12).

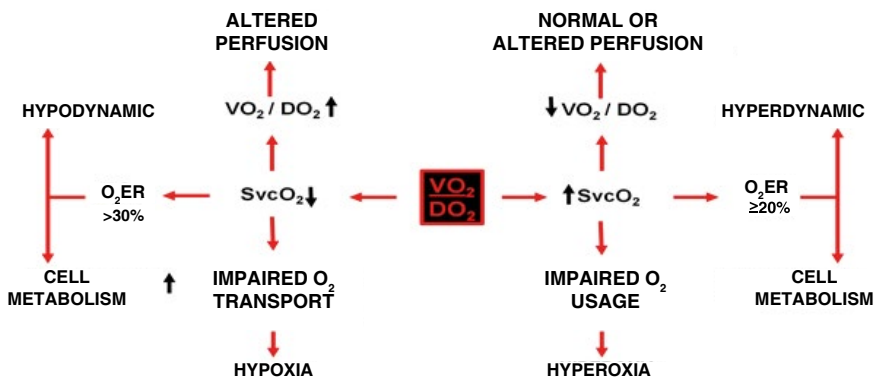
O2ER represents the amount (%) of oxygen consumed (extracted) by cells from arterial blood. Non-extracted oxygen returns through the venous circulation (SvcO2) to the right cardiac cavities for reoxygenation in pulmonary circulation. In non-pathologic conditions, O2ER of 20-30% is considered normal. Any rise in O2ER (low SvcO2) reflects increased cell metabolism (hypoxia); in contrast, a drop in O2ER (high SvcO2) reflects diminished cell metabolism (hyperoxia) (13,14). Defining hypodynamic or hyperdynamic requires looking beyond the clinical condition to include cardiac index < 2.5 L/min/m2, SvcO2 < 70% or O2ER > 30% (hypodynamic); or, conversely, cardiac index ≥ 4.0 L/min/m2, SvcO2 ≥ 80% or O2ER ≤ 20 % (hyperdynamic) (15,16) (Figure 2).

When a given SvcO2 value is analyzed, it involves the assessment of the interaction between all its determinants: 1) oxygen inflow, 2) transport 3) availability and 4) consumption (13) (Figure 3). To assess oxygen delivery and consumption in the tissues, knowledge of the following formulas is required (17):

$$DO2 = GC \times CaO2$$
$$VO2 = GC \times (CaO2 - CvO2)$$
$$EO2 = (CaO2 - CvO2) / CaO2 \; o \; (SaO2 - SvcO2) / SaO2 \; o \; VO2 / DO2$$
$$EO2 = (1 - SvcO2)$$
$$CaO2 = (Hb \times 1{,}34 \times SaO2) + (PaO2 \times 0{,}003)$$
$$CvO2 = (Hb \times 1{,}34 \times SvO2) + (PvO2 \times 0{,}003)$$

Where: CaO2 is arterial oxygen content and CvO2 is venous oxygen content.

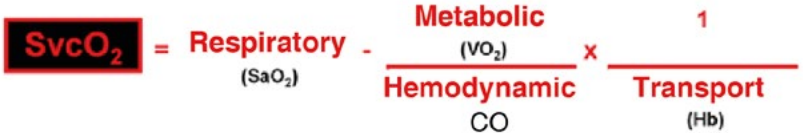
FIGURA 2. . Central venous oxygen saturation and oxygen consumption and availability ratio.



O2ER: oxygen extraction, SvcO2: central venous oxygen saturation, VO2/DO2: oxygen consumption/oxygen availability.

SOURCE: Authors.

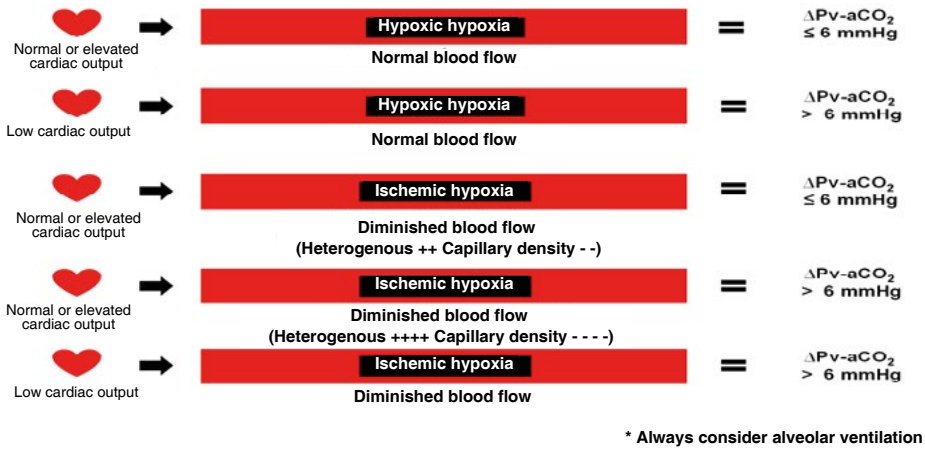
FIGURE 3. Determinantes de la saturación venosa central de oxígeno.



CO: cardiac output, Hb: hemoglobin, SaO2: arterial oxygen saturation, SvcO2: central venous oxygen saturation, VO2: oxygen consumption.

SOURCE: Authors.

FIGURE 4. Types of hypoxia.



Δpv-aCO2: carbon dioxide venous-to-arterial pressure delta, mmHg: millimeters of mercury.

SOURCE: Authors.

Venous-to-arterial carbon dioxide pressure difference (Δp(v-a)CO2)

Carbon dioxide (CO_2) provides even more valuable information on macro and microhemodynamics than oxygen (O_2) variables. CO_2 changes faster than lactate levels (18). It is the metabolic product of the Krebs cycle. In the context of aerobic metabolism, increased tissue CO_2 reflects greater oxidative metabolism or a higher intake of dietary carbohydrates (19). On the other hand, this increase in CO_2 may be due to greater anaerobic metabolism (20).

$\Delta p(v\text{-}a)CO_2$ is obtained by means of one central venous and one arterial blood gas measurement and it is the difference between venous pCO_2 and arterial pCO_2. Its normal value ranges between 2 and 6 mmHg (21). Changes in $\Delta p(v\text{-}a)CO_2$ are determined by the degree of blood flow (perfusion) and not by the degree of tissue hypoxia. Increases in $\Delta p(v\text{-}a)CO_2$ are associated with a reduction in tissue blood flow (ischemic hypoxia) in controlled settings, as long as adequate oxygen delivery to the tissues is ensured (22). When Fick's equation is applied to CO_2 metabolism, its clearance is found to depend on the difference between CO_2 content in venous blood ($CvCO_2$) and CO_2 in arterial blood ($CaCO_2$), multiplied by cardiac output or ($CvCO_2 - CaCO_2$) × CO. Consequently, the main determinant of changes in $\Delta p(v\text{-}a)CO_2$ is CO, and it is inversely proportional to it (23). Even at low CO, a patient can respond to hyperventilation with a normal or low $\Delta p(v\text{-}a)CO_2$ (24). Therefore, $\Delta p(v\text{-}a)CO_2$ depends on CO, $CvCO_2 - CaCO_2$ difference, VCO_2, alveolar ventilation and, to a lesser extent, on microcirculatory blood flow alterations. This means that $\Delta p(v\text{-}a)CO_2$ is a bedside surrogate of CO and microcirculatory blood flow. Studies have shown that, during hypoxic hypoxia (normal blood flow and lowered O_2 arterial pressure), $\Delta p(v\text{-}a)CO_2$ is < 6 mmHg; in contrast, during ischemic hypoxia (diminished blood flow and normal O_2 arterial pressure), $\Delta p(v\text{-}a)CO_2$ is > 6 mmHg (25) (Figure 4).

$\Delta p(v\text{-}a)CO_2$ reliably reflects CO variations in non-inflammatory shock states (hypovolemic, obstructive and cardiac), considering that the main change in blood flow is in the macrocirculation, unlike what happens in septic shock, where the main problem is microcirculatory blood flow, depending on capillary heterogeneity and density (26,27).

Venous-to-arterial carbon dioxide pressure difference/arteriovenous oxygen content delta (Δp(v-a) CO2/ΔC(a-v)O2)

The relationship between CO_2 production (VCO_2) and O_2 consumption (VO_2) is represented by the respiratory quotient (RQ = VCO_2/VO_2) which ranges between 0.6 and 1, depending on individual metabolic and energy conditions. In aerobic and resting conditions, VCO_2 is not greater than VO_2 and, therefore, the RQ is < 1; however, in anaerobic conditions, VCO_2 is greater than VO_2 resulting in a RQ > 1 (28,29). $\Delta p(v\text{-}a)CO_2/\Delta C(a\text{-}v)O_2$ is a useful surrogate of RQ = VCO_2/VO_2 since, according to Fick's equation, CO is present in the numerator and the denominator and cancels out, removing the blood flow component and leaving the venous-to-arterial CO_2 content difference ($\Delta Cv\text{-}aCO_2$) and the venous-to-arterial O_2 content difference ($\Delta Ca\text{-}vO_2$) as the main determinant, providing the RQ result without the need for indirect calorimetry. Because it is less invasive and offers a good correlation, $\Delta p(v\text{-}a)CO_2$ has replaced $\Delta Cv\text{-}aCO_2$ in obtaining $\Delta p(v\text{-}a)CO_2/\Delta C(a\text{-}v)O_2$ through one central venous and one arterial blood gas measurement, which allows to identify those patients in an anaerobic state (30,31) (Figure 5).

$\Delta p(v\text{-}a)CO_2/\Delta C(a\text{-}v)O_2 > 1$ is associated with microcirculatory abnormalities that lead to O_2ER reduction which, added to the drop in CO, results in a lower DO_2. Moreover, the increase in anaerobic CO_2 favors cell dysoxia (Figure 6). If shock is reverted promptly $\Delta p(v\text{-}a)CO_2/\Delta C(a\text{-}v)O_2$ can return to values < 1. Evidence suggests that improved microcirculatory blood flow distribution can revert anaerobic metabolism (32).

Elevated lactate does not always reflect tissue hypoxia or anaerobic metabolism and should, therefore, be used together with $\Delta p(v\text{-}a)CO_2/\Delta C(a\text{-}v)O_2$ in order to provide more accurate information at any point during patient assessment. $\Delta p(v\text{-}a)CO_2/\Delta C(a\text{-}v)O_2 > 1$ together with lactate > 2 mmol/L suggests tissue hypoxia and anaerobic metabolism with certainty, and should prompt the physician to optimize macro and microcirculation. In contrast, lactate levels > 2 mmol/L accompanied by $\Delta p(v\text{-}a)CO_2/\Delta C(a\text{-}v)O_2 <1$ require reassessing the origin of those levels and refraining from interpreting the result as tissue hypoxia or anaerobic metabolism (33-35). In 2016, in patients with septic shock admitted to our ICU, it was found that $\Delta p(v\text{-}a)CO_2/\Delta C(a\text{-}v)O_2 > 1.4$, measured 24 hours after admission, increases the risk of 30-day mortality by 5.49 (95% CI [1.07-28.09]), p = 0.04, and is an independent predictor of mortality. On the other hand, lactate was > 2 mmol/L in 93% of the patients who did not survive while only 43% of the survivors had lactate levels > 2 mmol/L, with a p value = 0.003 (36). A comparison carried out in 2019 in patients with normodynamic and hyperdynamic septic shock found higher anaerobic metabolism in hyperdynamic patients compared to normodynamic patients, with a $\Delta p(v\text{-}a)CO_2/\Delta C(a\text{-}v)O_2$ of 2.43 vs. 1.65, respectively; however, hyperdynamic patients had less microcirculatory blood flow alterations, with a $\Delta p(v\text{-}a)CO_2$ of 4.77 vs. 6.17 in normodynamic patients, although this could be accounted for by elevated CO and not necessarily by differences in microcirculation (37).

Changes in CO_2 (Haldane effect), hemoglobin concentration and tissue O_2ER influence $\Delta pv\text{-}aCO_2$ and $\Delta pv\text{-}aCO_2/\Delta Ca\text{-}vO_2$ despite preserved or even increased tissue perfusion. The most important counterargument has to do with the interaction on the CO_2 dissociation curve. Another important piece of information is the ideal cutoff point for $\Delta pv\text{-}aCO_2/\Delta Ca\text{-}vO_2$ which is not well defined, although

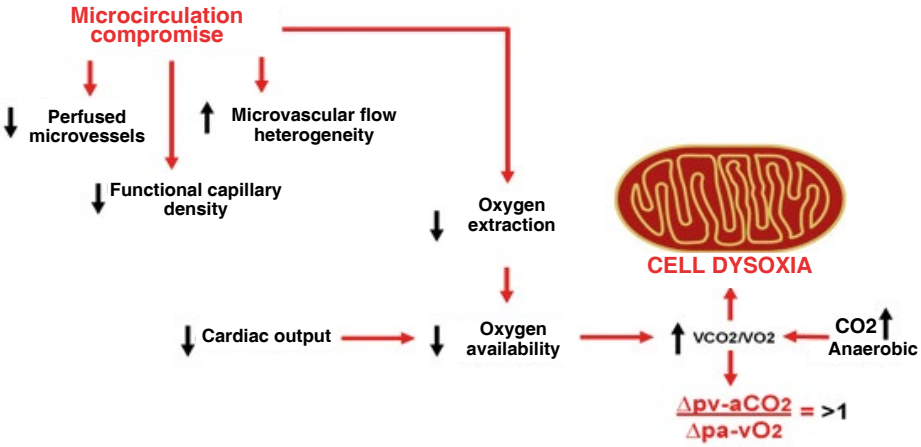
FIGURE 5. Simplified respiratory quotient formula.

$$RQ = \frac{VCO_2}{VO_2} = \frac{CO \times \Delta Cv\text{-}aCO_2}{CO \times \Delta Ca\text{-}vO_2} = \frac{\cancel{CO} \times \Delta Pv\text{-}aCO_2}{\cancel{CO} \times \Delta Pa\text{-}vO_2} = \frac{\Delta Pv\text{-}aCO_2}{\Delta Pa\text{-}vO_2} = 1$$

CO: cardiac output, RQ: respiratory quotient, VCO2: carbon dioxide production, VO2: oxygen consumption, ΔCavO2: arteriovenous oxygen content delta, ΔCv-aCO2: venous-to-arterial carbon dioxide content delta, Δpa-vO2: arteriovenous oxygen pressure delta, Δpv-aCO2: venous-to-arterial carbon dioxide pressure delta.

SOURCE: Authors.

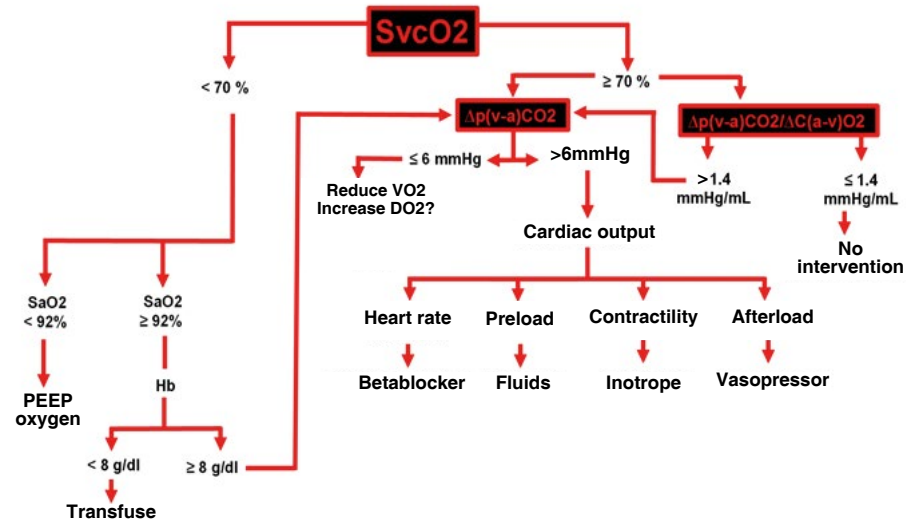
FIGURE 6. Events that determine cell dysoxia.



CO2: carbon dioxide, VCO2/VO2: carbon dioxide production/oxygen consumption, Δpv-aCO2/ΔCa-vO2: venous-to-arterial carbon dioxide pressure delta/arteriovenous oxygen content delta.

SOURCE: Authors.

FIGURE 7. Algorithm for hemodynamic monitoring based on two blood gases.



G/dL: grams/deciliter, Hb: hemoglobin, mmHg: millimeters of mercury, mmHg/mL: millimeters of mercury/milliliter, PEEP: positive end-expiratory pressure, SaO2: arterial oxygen saturation, SvcO2: central venous oxygen saturation, VO2: oxygen consumption, Δpv-aCO2: venous-to-arterial carbon dioxide delta, Δpv-aCO2/ΔCa-vO2: venous-to-arterial carbón dioxide pressure delta/arteriovenous oxygen content delta.

SOURCE: Authors.

it ranges between 1.4-1.68 mmHg/mL (38-40). Figure 7 shows the algorithm for hemodynamic monitoring using blood gas analysis.

CONCLUSION

Hemodynamic monitoring using blood gas analysis has been and will continue to be a bedside diagnostic tool that enables optimum and timely intervention. Whether static or dynamic, the ideal hemodynamic monitoring method does not exist. Measurement interpretations and decision-making will always be operator-dependent, creating advantages and disadvantages. Blood gas analyzers are readily available in any hospital, unlike sophisticated monitors. Δpv-aCO2 and Δpv-aCO2/ΔCa-vO2 are excellent markers or microcirculatory blood flow and anaerobic metabolism, respectively. Hemodynamic monitoring using two blood gases measurements is an option that allows to establish a diagnostic and therapeutic pathway and work on the premise of not more, not less, only what is needed.

ETHICAL RESPONSIBILITIES

Human and animal protection

The authors declare that no experiments were carried out in humans or animals for this research.

Data confidentiality

The authors declare having followed the protocols of their institution on patient data disclosure.

Right to privacy and informed consent

The authors declare that no patient data appear in this article.

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JSSD: Original idea, literature search, drafting of the development and conclusions sections, figure design and creation.
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GRS, EAMR, ORPN y MAGG: Literature search, development drafting.
DCOL: Literature search, development drafting, figure design.
EIZL: Literature search, development drafting, figure creation.
EMZ: Literature search, development drafting, figure design and creation.

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Conflict of interest

None declared.

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