Monitoring in pediatric cardiac critical care: A worldwide perspective

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Our ability to directly monitor the mechanisms that govern cellular function, oxygen use, and survival is minimal. Therefore, in critically ill children, surrogate markers are used to try to detect evolving or established hypoxia. These surrogate markers are best used in combination and are complementary to clinical examination. Regardless of resource limitations, we propose that the availability of certain monitoring tools form a standard of care without which pediatric cardiac critical care cannot be safely or optimally provided. These tools include standard invasive hemodynamic monitoring with electrocardiography, lactate measurement, central venous oxygen saturation, and echocardiography. Ultimately, monitoring is only useful when the clinician observes a specific value or trend and has the expertise to act appropriately. (Pediatr Crit Care Med 2011; 12[Suppl.]:S76–S80)

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"You see, but you do not observe."
—Sherlock Holmes. A Scandal in Bohemia: Sir Arthur Conan Doyle, 1891

Human beings are unable to store appreciable amounts of oxygen in their tissues. Consequently, a constant delivery must be maintained to preserve cellular function. The body achieves this through a series of elegant mechanisms, which closely monitor oxygen demand and delivery, detect any imbalance early, and elicit compensatory mechanisms to avoid hypoxia (1). Indeed, as early as 1872, a study by Pflueger suggested that variables such as arterial oxygen content, arterial pressure, velocity of blood flow, mode of cardiac work, and respiration are all incidental and subordinate; they all combine to service the cell (2, 3).

When this process is interrupted or overwhelmed by disease, demand can outstrip supply, leading to organ dysfunction, morbidity, and death (4–6). In critical care, the role of ensuring sufficient oxygen delivery to meet the metabolic needs of the patient then becomes the principal goal of the critical care physician. However, without the ability to directly monitor these intricate cellular processes, we use surrogate measures to detect hypoxia and ensure optimal outcomes.

The intent of monitoring in critical care is to alert the team to impending physiological derangements to avert organ impairment (3, 7, 8). The effectiveness of monitoring depends on our ability to interpret the clinical relevance of these variables and use this information to guide therapy. Although there are several sophisticated options, many of these are expensive and, in many areas of the world, monitoring capabilities are dictated by resource limitations. Faced with limited resources, one has to make choices based on answers to several questions. What techniques and equipment are available to monitor children in pediatric intensive care units? What are the essentials? What are luxuries? What monitors can one forego without placing patients at undue risk?

Controversy exists as to what constitutes essential monitoring and whether advanced and expensive techniques improve outcomes (9–12). Although evidence relating to this issue has been reviewed by several groups, no guidelines or recommendations have been proposed. There is therefore no consensus opinion as to the ideal approach to monitoring of patients in pediatric cardiac critical care.

This editorial is the first attempt to establish an international consensus as to what constitutes appropriate monitoring in pediatric critical care. We aim to provide guidelines that we believe should be achievable in most pediatric cardiac intensive care units around the world. However, we do not attempt to address the question of when these services should be provided. The majority of deaths worldwide in children occur in low-income countries and are most often related to infection, not congenital heart disease (13). In many low-income countries, considerably more lives will be saved by directing public healthcare funding toward low-cost, preventive interventions rather than complex initiatives such as pediatric cardiac programs (14). Nonetheless, many countries have seen dramatic declines in child mortality in the last two decades and pediatric cardiac programs could be provided in many of these areas.

This document represents our collective opinions as critical care physicians with experiences in Europe, Australia, Asia, Africa, and North America. The process initially involved an in-depth review of all the summaries of various modes of monitoring in contemporary intensive care described elsewhere in this supplement. Detailed discussion then occurred, highlighting individual preferences and practices while being cognizant of resource limitations in many parts of the world. This process resulted in pragmatic conclusions as to what would be reasonably achievable worldwide. We have summarized the characteristics of all individ-

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ual modalities and the reasons why we favor them. However, we have focused on the types of monitoring that we think are the most useful and affordable in relation to ensuring adequate oxygen delivery to meet metabolic demands.

Monitoring Options

In discussing these monitoring options, we assume that the support services to provide basic laboratory tests are readily available. We also assume that staff working in the intensive care unit have the skills and knowledge to use these monitors, interpret the data, and provide appropriate therapies for the postoperative cardiovascular surgical patient.

Standard Hemodynamic Monitoring

Heart rate, oxygen saturation, and blood pressure are easily obtainable and well understood. Appropriately named "vital signs," they should be constantly monitored throughout hospital admission. These simple parameters initially guide escalation and eventual de-escalation of therapy. Targets can be set for resuscitation. Trends as well as baseline values can both be useful. Continuous monitoring of heart rate and oxygen saturation along with intermittent noninvasive blood pressure and clinical examination can allow rapid assessment of volume resuscitation and respiratory support (15). Failure to respond favorably to initial interventions can rapidly identify patients who may require the next step in treatment or monitoring.

The importance of heart rate is underlined by the fact that the two principal determinants of cardiac output are heart rate and stroke volume. Tachycardia may reflect falling stroke volume or an increase in oxygen demand. Optimization of preload, afterload, and contractility should result in normalization of heart rate as a consequence of improved oxygen delivery with less myocardial work. In addition, reducing oxygen consumption by attenuating pain, anxiety, and hyperthermia can have an adjunctive effect by improving the balance between consumption and delivery (7, 16). Cardiac output can also be affected by ischemia, electrolyte disturbances, or dysrhythmias, which can be revealed by abnormal complex morphology on electrocardiogram.

Pulse oximetry is recommended for all critically ill patients. Its continuous nature and rapidity of change can alert the physician to a decrease in arterial oxygen saturation instantaneously and is often the first parameter to become deranged in an impending crisis (17, 18). In the general population of pediatric patients without complex congenital heart disease, brisk correction to establish high normal values improving oxygen delivery is necessary (19).

Invasive Blood Pressure Monitoring

Increasing fluid requirements or the need for vasoactive therapy and ventilation necessitates invasive arterial monitoring. This allows continuous pressure monitoring, waveform analysis, and repeated blood sampling for lactate and arterial blood gases. While aiming for a specific blood pressure can be initially useful, it is important to remember that pressure does not necessarily equate to flow, cardiac output, or oxygen delivery (7, 20). In the face of marginal myocardial performance, manipulating blood pressure by increasing the systemic vascular resistance can have a detrimental effect on cardiac output. This is especially important in single ventricle physiology, in which the cardiac output may fall precipitously in the face of a rising systemic vascular resistance. Relaxing blood pressure parameters in these cases may be indicated while monitoring other indices of oxygen delivery (21). An additional and useful function of invasive arterial monitoring is the information regarding cardiopulmonary interactions and preload responsiveness. Changes in arterial systolic or pulse pressure during the respiratory cycle with positive-pressure ventilation can predict which patients will have a rise in cardiac output in response to fluid therapy (22–25). It is important to remember that that not all children who demonstrate this feature benefit from further volume such as those with right ventricular failure (26, 27).

End-Tidal CO_2

End-tidal CO_2 is recommended for all ventilated patients in critical care, principally as a monitor of adequate ventilation, correct placement of endotracheal tubes, and as a marker of pulmonary blood flow (28). As well as providing information about alveolar ventilation, this continuous measurement may alter with cardiac output, shunt, and pulmonary blood flow (15, 29). The dead space created by in-line capnography with modern technology is negligible.

Lactate

Lactate is a widely accepted indicator of adequate global oxygen delivery. Available on most blood gas analyzers, this important measurement can be done routinely and at a relatively low cost, depending on its frequency. A rising value in a child with cardiac disease is likely to be reflective of inadequate oxygen delivery secondary to low cardiac output and is usually associated with an acidosis. A downward trend can indicate a favorable response to therapy and can be used as a guide to improve oxygen delivery. Normalization of serum lactate value is a specific goal of perioperative management. The first value recorded postoperatively, especially when combined with central venous saturations ($Scvo_2$), can be of prognostic significance (30, 31). Certain disadvantages with this parameter exist. First is its latent quality; a rise is usually secondary to established, rather than evolving, hypoxia. Second, increased levels may not always be associated with hypoxia with a sustained lacticemia being induced by β_2-agonists. Finally, lactate can be produced silently in areas of hypoxia as a result of low flow. A "normal" lactate therefore may only reflect its absence in the circulation, whereas there may be significant quantities present in the tissues.

As cardiac output and perfusion improves in the postoperative patient, accumulated lactate from this inflammatory process may "wash out." If this rise is transient in the face of other stable parameters, then it can be monitored. However, a sustained high level or rise is usually pathologic and should be aggressively treated. Serial measurements should be performed routinely in the postoperative patient and the trend should be closely observed for any subtle changes in clinical status.

Central Venous Pressure Monitoring

Central venous catheters are essential in many critically ill patients, especially smaller children after cardiac surgery. They facilitate drug delivery, blood sampling (for standard laboratory tests and

$Scvo_2$), waveform analysis, and pressure monitoring (central venous pressure). Careful interpretation of central venous pressure is essential. The assumption that pressure always equates to volume is incorrect because there is no linear relationship between these variables (32). Many factors alter this relationship, including, but not limited to, ventricular compliance, valvular regurgitation, atrioventricular dyssynchrony, and venous capacitance. Static measures of intracardiac filling pressures may not be helpful in determining preload responsiveness in critically ill patients, whereas dynamic changes in these values during spontaneous ventilation can be (33).

However, if the value is low or falling, in conjunction with other indices of inadequate cardiac output, it is reasonable to assess the response to a fluid bolus at the bedside. Continuous central venous pressure monitoring can be used to trend any response, favorable or otherwise. Guaranteed drug delivery and measuring venous saturations are perhaps of more value.

$Scvo_2$

Historically, the pulmonary artery catheter was regarded as the gold standard of hemodynamic monitoring, measuring both cardiac output and mixed Svo_2. However, concerns over safety, complications, and effect on outcome are such that it is not used routinely in critically ill patients, particularly children (34–36). Measuring a surrogate of Svo_2, $Scvo_2$ is now one of the most compelling monitoring tools within pediatric intensive care in terms of evidence and applied physiology. An immediate, inexpensive, and reproducible value, it quickly illustrates the basic physiologic response to any oxygen delivery/oxygen consumption imbalance or therapeutic intervention while alerting the physician to evolving hypoxia before other latent markers such as lactate become deranged (37, 38).

$Scvo_2$ measurements from a central line trends Svo_2 in most, but not all, situations (39–41). It is not affected by intracardiac shunts and can be used to establish the oxygen extraction ratio or arteriovenous difference in cyanotic children. Several studies have demonstrated its use in goal-directed therapy in both adult and pediatric studies treating sepsis and congenital heart disease (42–44).

It is important, however, to recognize the limitations of $Scvo_2$. Values may vary depending on the sampling site. As a marker of global oxygen delivery, it may be normal, or even high, in the face of regional perfusion abnormalities or impaired oxygen uptake and thus be falsely reassuring. Conversely, an abnormally low value is extremely specific for low cardiac output states and in the absence of significant anemia or hypoxia can be used as a therapeutic target (42, 45, 46).

Cardiac output can be determined using the Fick equation: cardiac output (CO) = oxygen consumption/arteriovenous difference. Many use $Scvo_2$ to represent cardiac output by using it to substitute oxygen consumption (CO = oxygen consumption/arterial oxygen content − $Scvo_2$). This is especially useful in the postoperative cardiac patient. Two things are important to note when monitoring this value. First, the relationship between $Scvo_2$ and CO is nonlinear (7, 40). Second, it is assumed that oxygen consumption and arterial oxygen content are stable. However, a drop in $Scvo_2$ in the otherwise stable child is likely to represent a fall in cardiac output and may require investigation. Continued monitoring of its trend in response to any intervention is mandatory. It helps to identify and manage a low cardiac output state, has become a therapeutic target in sepsis and the postoperative cardiac patient, and has prognostic value. It also can be used to improve oxygen delivery by guiding pulmonary output:systemic output and ventilation strategies (47, 48).

Traditionally, in most patients, improving arterial saturations will increase oxygen delivery and $Scvo_2$. However, in single ventricle physiology, the standard relationship between saturation and oxygen delivery becomes uncoupled. In addition to lung pathology, a fall in systemic oxygen saturation may reflect a fall in CO. A reduction in systemic oxygen delivery will result in a fall in venous saturations if oxygen consumption is stable. Subsequently, the saturation of the venous admixture (intracardiac "mixing" of systemic and pulmonary venous returns) will fall. Systemic saturations will follow because they are effectively one and the same.

$Scvo_2$ measurements provide vital information in patients with single ventricle physiology. With normal anatomy, CO is equal to the individual outputs from the pulmonary and systemic circulations: CO = pulmonary output = systemic output. In the single ventricle, the CO is now "divided," and the partitioning of flow depends on the relative resistances of the each circulation: CO = pulmonary output + systemic output. The Fick equation can therefore be devoted to each portion. If one combines and rearranges these equations, a simplified form that can be used at the bedside can be derived: pulmonary output/systemic output = 25 (95-SaO_2) (49). Therefore, targeting arterial saturations of approximately 75% to 80%, theoretically at least, assumes a satisfactory division of CO, adequate balancing of the circulation, and systemic oxygen delivery. However, oxygen delivery can alter widely in this patient group without a change in systemic saturation (50). This illustrates the importance of the valuable information regarding the adequacy of systemic oxygen delivery using $Scvo_2$. This may alter dramatically and sometimes inversely to changes in arterial saturations (21). Optimizing rather than normalizing arterial saturations in this group is paramount. There is no ideal value for $Scvo_2$ in these children, but a stable trend in conjunction with other markers of oxygen delivery is useful. Importantly, devotion to the perfection of balancing the circulation is irrelevant in the face of inadequate CO (51).

$Scvo_2$ can guide therapy in many different clinical situations. Serial measurements are therefore warranted in the unstable patient. $Scvo_2$ is invaluable when it comes to instigating and monitoring the effects of therapeutic intervention. Continuous real-time oximetry catheters are available, which can be either surgically placed or incorporated into a central venous line. Their use has been demonstrated in a number of studies but they are expensive (42, 43).

Measuring venous saturations is a standard of care that should be available in all pediatric cardiac centers and can be used in conjunction with other parameters and indicators of organ dysfunction.

Echocardiography

Echocardiography is an essential monitoring tool in cardiac critical care. It provides vital information regarding the hemodynamics of a critically ill child after cardiac surgery and should be performed in a timely manner prompted by a deterioration in other hemodynamic parameters or to evaluate a recent intervention. Echocardiography allows assessment of baseline and postoperative cardiac structure and function and quickly exclude early, treatable postoperative problems such as tamponade, shunt

occlusion, or residual lesions (52). Additional hemodynamic information such as CO, end-diastolic volume, global and regional ventricular function, and valvular abnormalities can also be obtained. More advanced techniques such as the use of tissue Doppler, speckle tracking, contrast, and three-dimensional echocardiography may become more established in the future (53–55).

These cannot be regarded as routine in pediatric critical care at the present time. Transthoracic echocardiography is a skill that can be achieved up to a certain standard by most intensivists (56, 57). It is safe, noninvasive, and has minimal consumable charges; however, intensivists should not perform echocardiograms independently unless they are comprehensively trained and accredited. There is no such thing as a "basic echo" in children. An inexperienced operator can obtain suboptimal images and misinterpret optimal ones. The clinical consequences of these mistakes can be profound.

Emerging Technology

Ever since questions were raised about the use and safety of the pulmonary artery catheter, the race has been one to try to find an alternative to the putative "gold standard" of hemodynamic monitoring. Since then, an array of potentially useful devices has emerged on the market. At present, the majority have not been recommended for use in children because of issues concerning calibration, size, training, assumptions, cost, and lack of validation.

The most promising of these monitors is near-infrared spectroscopy, a noninvasive device capable of displaying real-time regional tissue saturations. However, further studies need to be conducted before the role of near-infrared spectroscopy can be properly assessed in the pediatric critical care (58). Additionally, the cost of near-infrared spectroscopy hardware is currently prohibitive for many centers in low- or middle-income countries.

CONCLUSION

There is no single monitoring tool that alone can be described as the "gold standard" in pediatric intensive care. Shephard described the ideal characteristics of a monitoring system as accurate, reproducible with a rapid response, operator-independent, easy to use, no associated morbidity, continuous, and cheap (16). None of the monitoring described here fulfills these criteria in isolation. However, when used in combination, they may come closer to this ideal.

Naturally, physicians are drawn to newer technologies, which have an element of fascination. However, they are expensive, have little evidence to support their use, and can distract the clinician from doing the basics well.

To that end, we make the following recommendations for monitoring children after cardiac surgery, which should be achievable in most units around the world: 1) standard basic monitoring (heart rate, blood pressure, and arterial saturations) is indicated for all postoperative patients; 2) invasive lines are warranted in all but the simplest cases; 3) lactate and $Scvo_2$ should be regularly monitored along with frequent clinical assessment; and 4) echocardiography is indicated for any unexplained deterioration in clinical condition or monitoring parameters and remains one of the cornerstones of a successful pediatric cardiac surgical program.

Sherlock Holmes once remarked to his crestfallen colleague Dr. Watson: "You see, but you do not observe. The distinction is clear." We glance at monitoring and see the numbers all the time, but the continuous aspect of some parameters can be disabled by only viewing the monitors intermittently. Observing a trend over time is essential to detect subtle changes in these values, which may allow early detection of patient deterioration not obvious with intermittent snapshots. Ultimately monitoring, basic or otherwise, is only useful to the patient if the clinician observes a specific value or trend and has the expertise to act appropriately.

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