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Review

Hemodynamic monitoring of the critically ill neonate: An eye on the future

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SUMMARY

By continuous assessment of dynamic changes in systemic and regional perfusion during transition to extrauterine life and beyond, comprehensive neonatal hemodynamic monitoring creates numerous opportunities for both clinical and research applications. In particular, it has the potential of providing additional details about physiologic interactions among the key hemodynamic factors regulating systemic blood flow and blood flow distribution along with the subtle changes that are frequently transient in nature and would not be detected without such systems in place. The data can then be applied for predictive mathematical modeling and validation of physiologically realistic computer models aiming to identify patient subgroups at higher risk for adverse outcomes and/or predicting the response to a particular perturbation or therapeutic intervention. Another emerging application that opens an entirely new era in hemodynamic research is the use of the physiometric data obtained by the monitoring and data acquisition systems in conjunction with genomic information.

1. Introduction

Neonatology continues to evolve rapidly along with advances in other subspecialties, biomedical research and cutting edge biomedical technology. However, our understanding of neonatal hemodynamics and, as importantly, when and how to intervene when deviations from the physiologic course occur remain quite limited. In this context, the old story of six blind men and an elephant comes to mind [1] (Fig. 1). Probably, each of us has come across this parable in one form or another and the lesson it is meant to teach can be applied to many areas of our lives. Accordingly, it very well describes the limitations of our understanding of neonatal cardiovascular physiology and pathophysiology, with vast differences in opinions and ongoing debates about how to approach the numerous challenges that the neonatologist faces when providing care for neonates with hemodynamic compromise.

Severe cardiovascular compromise in the neonatal period is associated with increased morbidity and mortality [2–6]. Despite many attempts to define neonatal hypotension [7–13] and develop criteria for initiating interventions [14] using various approaches and vasoactive medications [15–18], these and other related questions remain mostly unanswered. Importantly, clinical trials on treatment of neonatal hypotension have so far failed to demonstrate improvement in clinically relevant long-term outcomes.

Some of the major underlying challenges include the heterogeneity of the neonatal population due to differences in gestational age (GA) and postnatal age, variations in maturity for a given GA, existing comorbidities (particularly lung disease and infection), complex and multifactorial interactions between systemic and regional perfusion [19] and underlying genetic heterogeneity. In addition, conventional hemodynamic parameters [heart rate (HR), arterial oxygen saturation (SpO_2), and blood pressure (BP)], even if monitored continuously, have significant limitations for accurate assessment of both the hemodynamic status and the response to interventions used for the treatment of the circulatory compromise. Recognition of shock in its early, compensated phase along with identification of the underlying pathophysiology is of paramount importance in reversing shock before its progression to uncompensated cardiovascular failure when the obvious clinical manifestations of shock become apparent. This requires, among others, the use of comprehensive hemodynamic monitoring systems capable of continuous and simultaneous acquisition of multiple

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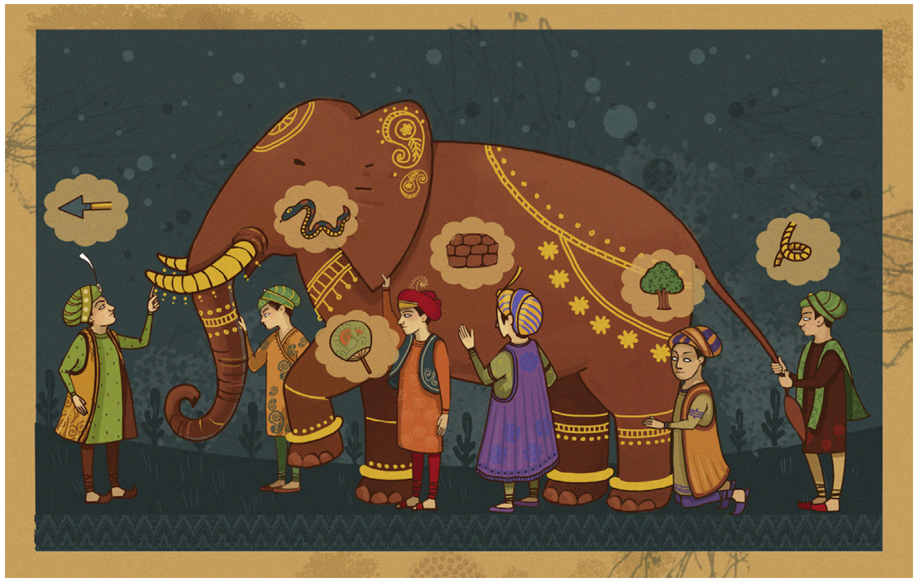

Fig. 1. "We have to remember that what we observe is not nature in itself, but nature exposed to our method of questioning" – Werner Heisenberg, 1958 [1].

hemodynamic parameters that reflect both systemic and regional blood flow and oxygen delivery [20–22].

2. Comprehensive hemodynamic monitoring

With advances in biomedical technology and computer science, the ability of hemodynamic monitoring systems to collect, store, and analyze the complex physiometric data provides a foundation for advances in diagnosis and management of neonatal cardiovascular compromise. However, it must be emphasized that this system also has a number of caveats concerning its accuracy, reliability, feasibility, and the need for validation across different subpopulations [21,22]. The utility power of such monitoring systems lies in the comprehensiveness of the hemodynamic parameters monitored beyond the conventionally obtained parameters of HR, respiratory rate (RR), SpO_2, BP, and transcutaneous CO_2 measurements. For blood pressure monitoring, invasive continuous monitoring via umbilical arterial catheter (UAC) or peripheral arterial line remains the preferred method [23,24]. The macrocirculatory component of systemic perfusion can be assessed by measurement of cardiac output (CO). Whereas functional magnetic resonance imaging (fMRI) has become the "gold standard," its feasibility even for research purposes remains limited. Bedside functional echocardiography (fECHO) and impedance electrical cardiometry (IEC) have been used at the bedside and these methods provide comparable CO measurements [25,26]. Impedance electrical cardiometry has the additional advantage of the capability of continuously assessing CO. Whereas newer methods of non-invasive cardiac output monitoring are emerging [27,28], further validation of IEC and validation of the newer methods in the neonatal population are needed, particularly in extremely preterm neonates. For assessment of peripheral perfusion and microcirculation, a number of methods are currently available, such as laser Doppler flowmetry, visible light technology, orthogonal polarization (OPS) and side-stream dark-field (SDF) imaging. Inclusion of perfusion index (PI) [29–32] as additional parameter derived by pulse oximetry into the hemodynamic monitoring system can potentially also improve the assessment of peripheral perfusion, although such use in neonates remains to be robustly validated. To evaluate regional organ blood flow, near-infrared spectroscopy (NIRS) is a useful tool for non-invasive and continuous assessment of tissue oxygen saturation. Tissue oxygenation index (TOI), with caution, can be used as a surrogate of organ blood flow [20,33]. For more in-depth overview of the methods used for monitoring of the different cardiovascular parameters and the corresponding references in the literature, we encourage the reader to read previously published reviews on the topic [20–22].

Beyond monitoring blood flow and oxygen delivery to the tissues, simultaneous assessment of functional activity of target organs is an additional important step to enhance the diagnostic power of comprehensive hemodynamic monitoring systems. Amplitude-integrated electroencephalography (aEEG) has been studied primarily in term neonates with hypoxic–ischemic encephalopathy [34–36]. However, studies have recently also been published on its use in preterm neonates [37,38] along with studies on the correlation of brain activity patterns with NIRS data for diagnostic and prognostic purposes [39,40]. These latter findings lend support to the idea of integrating aEEG into hemodynamic monitoring and data acquisition systems.

A hemodynamic monitoring "tower", such as that designed and described by the authors [21,22], allows for practical continuous and simultaneous bedside monitoring and acquisition of the synchronized physiologic data at high sampling rates in real time. It also has the advantage of being a mobile, stand-alone unit that can be utilized at the patient's bedside. Collected data are subsequently analyzed to study minute-to-minute changes and interactions between multiple hemodynamic parameters.

For research applications on a larger scale, the output data from bedside monitors and other devices (e.g. infusion pumps, ventilators) from multiple patients can be acquired and routed to central servers using hospital data networks. Preprogrammed software for hospital-wide systems is available from third-party vendors [e.g., Bernoulli Enterprise (Cardiopulmonary Corporation, CT, USA) or BedMaster (Excel Medical Electronics, FL, USA)]. Of note, their implementation, in addition to financial cost, is a challenging and