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Haemodynamic Monitoring and Management in Children

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During the past 20 years, intensivists and anaesthesiologists have faced tremendous changes in the way haemodynamic monitoring and management is performed in adult patients. The use of the pulmonary artery catheter has dramatically decreased, leaving a strong reliance on less or non-invasive technologies that mainly rely on transpulmonary thermodilution, pulse contour analysis, bioimpedance-bioreactance, and Doppler technologies. Functional haemodynamic monitoring, which focuses on the effects of stress on a particular haemodynamic parameter rather than on the haemodynamic parameter itself, has dramatically increased. Moreover, haemodynamic management has been strongly impacted by the concept of "Goal Directed Therapy" related to the optimisation of parameters such as cardiac output, venous oxygen saturation, and dynamic parameters of fluid responsiveness (pulse pressure variation, stroke volume variation, or plethysmographic waveform variation) (Rivers et al. 2001; Hamilton et al. 2010; Cannesson 2010).

Despite the numerous improvements observed in the adult patients, haemodynamic monitoring in children remains poorly investigated. This population presents specific characteristics that make the implementation of haemodynamic monitoring technologies challenging. First, the paediatric population includes a wide spectrum of age, size, and weight. Second, the most commonly used technologies in adults are not yet designed for children. Third, vascular access in children (especially in infants and neonates) can be challenging and most haemodynamic monitors are not designed for this population. Fourth, the cardiovascular physiology observed in children (especially in the paediatric cardiac intensive care unit) makes implementation of technologies using thermodilution extremely difficult. And finally, because the haemodynamic data recorded in children are significantly lower than those measured in adults (cardiac output), the accuracy of these haemodynamic monitors is constantly challenged.

However, despite these potential difficulties, clinicians still have the opportunity to use and implement haemodynamic technologies in the paediatric patient. Because certain technologies are available in this setting, it is more likely that protocols for specific haemodynamic goals will be developed in the near future.

Basic Cardiovascular Physiology Applied to the Clinical Setting

As described by Arthur Guyton in his textbook of medical physiology, one of the main goals of the circulation is to bring oxygen to the body tissues. To be achieved, this goal requires two physiological objectives: An adequate perfusion pressure in order to force the blood into the capillaries of the organs, and an adequate flow to deliver oxygen to the tissues (Guyton and Hall 2006). Interestingly, if arterial pressure is monitored everyday in the intensive care unit and in the anaesthesiology setting, cardiac output is rarely monitored. However, arterial pressure does not provide any relevant information regarding cardiac output. The relationship between these two parameters is complicated and far from being linear. Consequently, there is a need for cardiac output monitoring technologies in these settings.

Invasive Arterial Pressure Monitoring

In children, a few specifics have to be kept in mind regarding invasive arterial pressure measurements. First, because heart rate is much higher than in adults and because arterial pressure is lower, measuring this parameter requires high fidelity tracings. Second, because the vascular compliance is higher in kids than in adults, invasive arterial pressure readings are impacted: Systolic arterial pressure has a tendency to be lower while diastolic arterial pressure has a tendency to be higher. Finally, the most reliable arterial pressure parameter measured invasive ly in children under six years old is the mean arterial pressure.

Cardiac Output Monitoring

Cardiac output is the product of stroke volume and heart rate. Stroke volume in children (as well as in adults) depends on ventricular contractility, preload, and afterload. In neonates and infants, there is a very low reserve of contractility because of the immaturity of the cardiac muscle. Consequently, the ventricles are very sensitive to acute changes in afterload. Another consequence of this immaturity is that the adjunction of inotrope has very little effects on the ventricular contractility. Consequently, the most efficient way to increase cardiac output in this setting is to increase heart rate. The immature heart is thus chronotrope dependent. Several devices have potential to be used for cardiac output monitoring in children (See Table 1).

Thermodilution– Pulmonary Artery catheter

The pulmonary artery catheter remains the gold standard for cardiac output monitoring in adults. It relies on thermodilution and on the Stewart Hamilton principle. It's a highly invasive method with very few remaining indications in the paediatric critical care setting (mostly paediatric cardiac transplantation). The minimum size limit for the use of the pulmonary artery catheter in children is 3 to 5 kgs. However, the correct positioning of this catheter in children under 10 kgs of body weight is particularly challenging, even in trained hands. The main advantages of this technique in the paediatric setting is the accuracy of the device, and its ability to allow for SvO_2 and pulmonary artery pressure monitoring in children.

Transpulmonary Thermodilution

Currently, two distinct devices allow for transpulmonary thermodilution: The PiCCO system (Cecchetti et al. 2003; Fakler et al. 2007) and the EV1000. The PiCCO system has been tested in several paediatric clinical studies with positive results. The system requires a dedicated femoral arterial line and a central venous catheter placed in the superior vena cava territory. This system has been validated against the aortic flow probe in paediatric animal models, and against the Fick method, and the pulmonary artery catheter in human paediatric studies that displayed positive results (McLuckie et al. 1996; Bajorat et al. 2006; Pauli et al. 2002). The major advantage of this technique is that it also allows for continuous cardiac output monitoring using pulse contour analysis. The pulse contour analysis method is calibrated against the transpulmonary thermodilution data and is accurate enough in the absence of acute changes in systemic vascular resistances. Moreover, this technique provides additional important haemodynamic information such as pulse pressure variation, stroke volume variation, global end diastolic volume, and extra vascular lung water (Lemson et al. 2009). Consequently, this system can be qualified as an advanced haemodynamic monitoring device. In term of size, the device is designed for any weight. However, most studies have focused on children weighing more than 3 – 5 kgs.

Lithium Dilution

The LiDCO device offers the lithium dilution technique. This system only requires an arterial line and has no size limit. One must keep in mind that Lithium injection presents a few contra indications: lithium therapy (exceptional in children) and neuromuscular blockade. This system has been tested and validated in several paediatric clinical studies with positive results (Kurita et al. 1997; Linton et al. 2000).

Ultrasound Techniques

Several ultrasound techniques have been developed and are available. The most widely recognised and most accurate is the transthoracic echocardiography. Transo - esophageal echocardiography is also feasible, especially in the operating rooms, and the size limit for this technique is around 3 – 5 kgs; however, there is no size limit for transthoracic echocardiography. This technique is very well validated and is an extremely reliable tool for measuring cardiac output and also for evaluating left and right ventricular functions, valves, and other cardiac structures and functions. It's a completely non-invasive technique. The main limitation is related to the relative complexity of performing a comprehensive and reliable exam. Echocardiography requires an extensive training and presents evident inter and intra observer variability. Moreover, echocardiography cannot be considered as a continuous haemodynamic monitor but rather as an intermittent monitoring that is able to provide the most comprehensive cardiac evaluation.

Other ultrasound techniques are represented by the oesophageal Doppler and by the USCOM device. The USCOM device allows recording aortic flow through a suprasternal Doppler technique and is completely non invasive (Knirsch et al. 2008). Both have been validated in paediatric human studies. The oesophagealDoppler allows for continuous monitoring while the USCOM device is an intermittent monitor. Both of these devices require some expertise and training before use. However, just to make note, both of these devices only measure the flow in the descending aorta.

Other Cardiac Output Monitoring Techniques

Several other cardiac output monitoring technologies, especially non-invasive technologies, are now available. Electrical techniques such has bioimpedance and bioreactance have been developed initially in adults and then in children. These techniques are not yet completely validated but surely represent an interesting future.

Also, ultrasound dilution techniques have been described recently. These systems allow for continuous cardiac output monitoring in the intensive care unit. They rely on an extracorporeal system and on ultrasound dilution measurements. They are not fully validated yet, but the preliminary studies show interesting results. These systems could potentially be able to monitor cardiac output in patients with intracardiac shunts and/or abnormalities, which is not feasible with most thermodilution techniques.

Dynamic Parameters of Fluid Responsiveness in Children

Dynamic parameters of fluid responsiveness allow for accurate prediction of fluid responsiveness (i.e. they predict the effects of volume expansion on cardiac output). In patients under mechanical ventilation and general anaesthesia, the most popular dynamic parameters are either derived from the arterial pressure waveform (pulse pressure variation, stroke volume variation) or from the plethysmographic waveform (respiratory variation in the plethysmographic waveform amplitude). These parameters have been tested in several clinical studies in adults and have consistently been demonstrated as the best predictors of fluid responsiveness (and superior to central venous pressure or wedge pressure). Only a few studies have been performed in children so far and most of them seem to demonstrate that stroke volume variation is a strong predictor of fluid responsiveness (with a threshold value between 10 and 15 percent), while peripheral parameters such as pulse pressure variation and plethysmographic waveform variation fail to predict fluid responsiveness in this setting (Durand et al. 2008; Pereira de Souza Neto et al. 2011; Renner et al. 2011). The most convincing explanation is that arterial compliance in children is so high that even if respiratory variations in stroke volume are important, the respiratory variations in arterial pressure are absorbed and then fail to predict fluid responsiveness. As a consequence, only stroke volume variation can be considered as a good predictor of fluid responsiveness in children. Just to make note, only stroke volume variation obtained using echocardiography has been found to be predictive. Stroke volume variation derived from the arterial pressure waveform may be impacted by arterial compliance and thus, may be inaccurate.

Central Venous Oxygenation (SvO2)

Central venous oxygenation depends on cardiac output, haemoglobin, SaO2, and oxygen consumption. Consequently, SvO2 is a synthetic parameter that provides a global view on haemodynamic. Recently, central venous catheters allowing for ScvO2 monitoring (venous oxygenation from the superior vena cava) have been developed for children (Liakopoulos et al. 2007). This device has been tested against co oximetry with very good results. The use of these parameters has also been tested with positive results in an outcome study that focused on children with septic shock, following the methodology of the Rivers study conducted in adults. In addition, SvO2 monitoring in children with congenital heart disease and intra cardiac shunts allows for measuring the ratio between the pulmonary flow and the systemic flow (Qp/Qs=[SaO2 – SvO2]/[SvpO2 – SaO2]) where SvpO2 is the oxygen saturation in the pulmonary vein and is considered to be 100 percent.

Integration of the Haemodynamic Parameters Together in the Paediatric Setting

As in adults, haemodynamic monitoring and management in children cannot only rely on arterial pressure. There is a need for cardiac output and oxygenation parameters monitoring. Depending on the setting (anaesthesiology, intensive care unit), the choice of the haemodynamic monitoring solution will be different. Low risk situations will more likely require non-invasive technologies while high-risk situations will require a more in-depth understanding of the physiology, and consequently will need more invasive solutions. Cardiac output should be used more often in the management of these patients because arterial pressure alone does not provide the full picture. In addition,ScvO2 monitoring can help in driving the resuscitation more efficiently. In the future, it is more likely that regional haemodynamic monitors will progressively appear. Today, some systems that rely on Near Infrared Spectroscopy have been proposed for monitoring regional oxygenation with encouraging results (cerebral, hepatic, or renal). It is more likely that the future of haemodynamic monitoring in children will involve more accurate and less invasive technologies as well as more integrative approaches using different parameters (from global haemodynamic parameters to regional haemodynamic parameters).

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