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Critical Care Update

Hemodynamic Monitoring: Part 2

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Squara P, Cecconi M, Rhones A, et al. Tracking changes in cardiac output: methodological considerations for the validation of monitoring devices. *Intensive Care Med*. 2009;35:1801-1808.

Measurement of cardiac output provides clinical information useful for diagnosis and therapeutic support of patients with hemodynamic abnormality or instability. Many new devices have come online in recent years. As these devices are introduced, there is a need for validation and evaluation of usefulness in the clinical setting. With the evolution of new technologies, the methodology behind evaluation of new tools becomes ever more important.

To provide support for a new cardiac output monitor, many authors compare the cardiac output measurements obtained with a new technology with a reference technology at multiple time points. There are a number of limitations with this approach. In particular, there are limits for the estimation of bias and interpatient variability. Frequently, precision and time response are not taken into consideration. Perhaps most important, the reference technology must be considered superior to the studied technology. Clearly, there are times when this is not the case.

Physicians trust a given value if a device is accurate, and they trust in the change of this value if the device is precise. An acceptable device for cardiac output monitoring must fulfill 2 traditional quality criteria required for cardiac output measurements: high accuracy and high precision. Accuracy reflects the comparison of a new device with an accepted standard. Precision is best considered as the variability of data obtained because of random errors in measurement. Precision is sometimes improperly used for interpatient variability of bias, which is the systematic difference between 2 measurement techniques. Precision is also sometimes improperly used to describe global variability of measurement that may include the following: 1) true accuracy of a monitoring system, 2) physiological intrapatient variability of the measured variable, 3) artifacts, 4) interpatient variability when data from different patients are pooled together, and 5) interdevice variability when using different machines. Precision is an intrinsic system property independent from bias and does not require a reference method to be analyzed. (The reader may encounter Bland-Altman analysis, which quantifies the bias or systematic difference between 2 measurement systems or devices.)

In addition to accuracy and precision criteria, validation of a monitoring device must consider changes in the monitored variable over time. Good time response and accurate response amplitude are valuable qualities in data obtained. We accept a margin of error (tolerance) for accuracy, precision, and time response, but the cumulative effect of these errors may affect the clinical usefulness of the monitoring device. Estimation of sensitivity and specificity in the detection of significant directional change is another important criterion in the evaluation of the reliability of a device.

In order to generalize the results of a validation study, patients must be representative of the population in whom the device is likely to be used. In critical care, new monitoring devices should be tested in patients with sepsis and nonseptic conditions, spontaneous and mechanical ventilation, vasoactive drugs, or vasodilators. In addition, the population studied must have a high likelihood of changes in cardiac output during the study period.

Validation of a new technology requires independent validation of the quality criteria listed previously against a specific gold standard giving instantaneous exact values. In practice, one often sees limited assessment of clinical acceptability of a new technology by comparison with a widely used reference technology based on standard quality criteria. A cardiac output gold standard is necessary to assess the accuracy and amplitude of response in cardiac output monitoring systems. Unfortunately, a true gold standard for cardiac output accuracy in the clinical setting is often lacking. Instead, a widely used technology known to provide “acceptable” accuracy is taken as the reference for comparison. In clinical practice, the bolus thermodilution technique as performed with a pulmonary artery catheter (PAC) has historically been accepted as a reference method. However, this technique requires manual intervention and may have intra- and interinvestigator variability.

Because no cardiac output monitoring device has fulfilled an independent ideal validation of all the quality criteria described previously, there is a lack of consensus regarding reference technology. The clinical global acceptability of a studied technology must be validated against a comparable system using real-time, automatic, and continuous data that are completely understood. A cardiac output monitoring device should ideally provide reliable data to track long-term changes and also generate snapshot information. In contemporary practice, the continuous output PAC is the most commonly used reference technology against which other technologies are evaluated.

A completely automatic, continuous data collection technique should be used for both new and reference technologies

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to avoid errors inherent to the collection of large amounts of data and limit interobserver variability. Time sampling may be an issue when comparing 2 devices using different technologies. The data acquisition process is fraught with complications. All manufacturers must compromise between a rapid time response in data collection and variability of results. A smaller sampling time or more rapid data acquisition is associated with greater variability in results.

Before analyzing data collected in a comparison of technologies, it is important to validate the data obtained. Limitations must be prospectively determined based on knowledge of both the new and reference technologies. For example, periods of time when patients are agitated, when 1 or both systems become disconnected, or when there is clear evidence of a situation leading to unrealistic results must be identified. This step in validation may be altered by user input. Ideally, data are evaluated by an independent assessor who is blinded to the choice of monitoring technology. Situations in which unrealistic results are found must be studied separately. This will be helpful to identify specific limitations of a device.

Marik PE. Noninvasive cardiac output monitor: a state-of-the-art review. *J Cardiothorac Vasc Anesth*. 2013;27:121-134.

Dries D. Cardiac output monitors: old and new. *J Burn Care Res*. 2013;34:543-548.

Critically ill patients are poor candidates for fluid administration if no benefit is shown. Stroke volume and cardiac output measurements are contemporary guides for hemodynamic management. In recent years, alternative technologies to the PAC have been developed that are less invasive and reported to better define both cardiac output and responsiveness to changes in preload. Arterial pulse contour evaluation is the essence of several new technologies based on the relationship of blood pressure, stroke volume, arterial compliance, and systemic vascular resistance. Three systems using pulse contour evaluation have been marketed and evaluated. The Lithium Dilution Cardiac Output (LiDCO, Cambridge, UK) system and the Pulse Contour Cardiac Output (PiCCO, Munich, Germany) system use indicator dilution cardiac output measurement to calibrate pulse contour assessment. Pulse contour analysis is combined with patient demographic and physical characteristics for arterial impedance estimation in the FloTrac system (Edwards Lifesciences, Irvine, CA). These 3 systems report stroke volume variation and pulse pressure variation. Changes of pulse pressure and stroke volume under different preload conditions allow evaluation of fluid responsiveness.

Invasive blood pressure measurement (an arterial catheter) is critical to effective pulse contour assessment. The site of blood pressure measurement is an important factor in interpreting cardiac output measured by pulse contour systems. Discrepancies among central and peripheral blood pressure have been described in clinical situations such as the patient coming off cardiopulmonary bypass, septic shock, vasoactive drug administration, and liver transplantation. Differences in blood pressure measured with catheters at different arterial sites may be significant, thus misrepresenting true aortic pressure giving abnormal cardiac output values.

The LiDCO system combines traditional indicator dilution measurement of cardiac output with lithium as the indicator with pulse contour evaluation in which the arterial pressure waveform is used to describe the volume of the arterial bed. Stroke volume is determined from arterial waveform analysis as calibrated by lithium indicator dilution measurement of cardiac output. Lithium is a convenient material to use because it may be injected into a peripheral vein, and the doses required do not exert pharmacologic effects.

The PiCCO system combines pulse contour analysis with transpulmonary thermodilution cardiac output. To determine transpulmonary cardiac output, central venous and central arterial catheters are required. Transpulmonary cardiac output measurement with PiCCO technology has been reliable in comparison with PAC thermodilution in a variety of patients. Stroke volume may be calculated with this technology from the area under the systolic portion of the arterial waveform. The reliable shape of the arterial waveform, arterial compliance, systemic vascular resistance, and device-specific calibration are required by this system. Arterial compliance is derived from systemic vascular resistance and the shape of the diastolic portion of the arterial waveform. PiCCO uses transpulmonary cardiac output evaluation for calibration. Like the LiDCO device, PiCCO technology measures stroke volume variation and pulse pressure variation, which predict fluid responsiveness. However, as noted previously, central venous and femoral arterial catheters are required, leading some observers to question whether this is a truly noninvasive monitor.

FloTrac systems include a sensor and corresponding monitor unit. The system is operator independent and has been quite popular. Only a peripheral arterial catheter is required. FloTrac is based on the assumption of a linear relationship between pulse pressure and stroke volume. Vascular compliance is an important part of these calculations. This variable is determined by demographic data for the patient and waveform characteristics evaluated from the arterial pressure waveform. This technology does not have good agreement with thermodilution, at least in early-generation devices. Patients with low systemic vascular resistance (sepsis) gave measurements that were unreliable.

Studies performed in the operating room suggest that pulse pressure variation and stroke volume variation based on pulse contour analysis are predictive of fluid responsiveness. Principles underlying this assertion are based on physiologic changes during positive pressure ventilation. Intermittent positive pressure breaths cause cyclic changes in loading conditions of the left and right ventricles. Inflation decreases preload and increases afterload of the right ventricle. A decrease in right ventricular preload and an increase in right ventricular afterload create a decrease in right ventricular stroke volume. This is associated with a decrease in left ventricular filling after a lag of 2 to 3 heart beats. Cyclic changes in right ventricular and left ventricular stroke volume are greater when the ventricles operate on the steep portion of the Starling curve. Thus, the magnitude of respiratory changes in left ventricular stroke volume is indicative of biventricular preload dependence.

Comparison of the 3 systems described has occurred. Methodologic problems limit the quality of much of these data. In general, the LiDCO and PiCCO systems provide better comparison with PAC thermodilution than FloTrac.

Devices using bioimpedance and bioreactance offer an alternative noninvasive method for cardiac output evaluation. Bioimpedance systems apply a high-frequency electric current of known amplitude across the thorax and measure changes in voltage of the returning signal compared with the initial signal. The ratio between voltage and current amplitudes is a reflection of transthoracic resistance and varies in proportion to the amount of fluid in the thorax. The instantaneous rate of change of resistance to current flow is thought to be related to blood flow in the aorta. Unfortunately, this approach has been found to be inaccurate in the critical care unit and cardiac catheterization laboratory. Problems also are seen in settings in which significant (electrical) noise and body motion exist and in patients