Pressure Waveform Analysis

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Monitoring cardiac output is of special interest for detecting early hemodynamic impairment and for guiding its treatment. Among the techniques that are available to monitor cardiac output, pressure waveform analysis estimates cardiac output from the shape of the arterial pressure curve. It is based on the general principle that the amplitude of the systolic part of the arterial curve is proportional to cardiac output and arterial compliance. Such an estimation of cardiac output has the advantage of being continuous and in real time. With "calibrated" devices, the initial estimation of cardiac output by pressure waveform analysis is calibrated by measurements of cardiac output made by transpulmonary thermal or lithium dilution. Later, at each time transpulmonary dilution is performed, the estimation by pressure waveform analysis, which may drift over time, is calibrated again. By contrast, uncalibrated devices do not use any independent measurement of cardiac output. Unlike calibrated devices, they can be plugged to any arterial catheter. Nevertheless, uncalibrated devices are not reliable in cases of significant short-term changes in arterial resistance, as for instance in patients undergoing liver surgery or those with vasodilatory shock receiving vasopressors. Perioperative hemodynamic monitoring is recommended for high-risk surgical patients since it reduces the number of complications in these patients. The pressure waveform analysis monitoring, especially with uncalibrated devices, is suitable for this purpose. In the intensive care setting, hemodynamic monitoring is recommended for patients with acute circulatory failure, who do not respond to initial therapy. Since these patients often experience large changes in arterial resistance, either spontaneously or due to vasoactive drugs, calibrated devices are more suitable in this context. Not only are they more reliable than uncalibrated devices but also they provide a comprehensive hemodynamic assessment through measurements of a variety of transpulmonary thermodilution-related variables. In this review, we summarize the characteristics of the monitoring devices using the pressure waveform analysis and discuss the appropriate use of different devices in the perioperative and intensive care unit settings. (Anesth Analg 2017;XXX:00–00)

Cardiac output (CO) is the key determinant of oxygen delivery and the lever of action of 2 major therapies of hemodynamic instability, fluids, and inotropes. It is now recommended to monitor CO in high-risk surgical patients[1] and in patients with shock not responding to initial therapy.[2]

Almost 50 years after the emergence of the pulmonary artery catheter, many techniques are available for monitoring CO. Among them, the pressure waveform analysis (PWA) estimates CO from the shape of the arterial pressure curve.

AVAILABLE TECHNIQUES

All available devices use the principle that the amplitude of the systolic part of the arterial pressure curve in the aorta is proportional to stroke volume and inversely proportional to arterial compliance. Such estimation requires an accurate geometric analysis of the peripheral "pulse contour," and some reliable assumptions regarding the physiologic characteristics of the arterial tree. It also depends on the quality of the arterial pressure signal. The available devices differ in 2 aspects. First, some of them require an external calibration, whereas others do not. Second, some devices analyze an arterial curve that is obtained through an indwelling catheter, while some others analyze a pressure waveform that is estimated noninvasively. In all cases, the precise algorithms they use are kept secret by their constructors.

INVASIVE CALIBRATED PWA DEVICES

Systems Calibrated by Transpulmonary Thermodilution

Two devices calibrate PWA by transpulmonary thermodilution: the PiCCO system, (Pulsion Medical Systems, Feldkirchen, Germany) and the VolumeView system (Edwards Lifesciences, Irvine, CA).

Transpulmonary thermodilution consists of injecting a bolus of cold saline through a subclavian or internal jugular catheter and in estimating CO by analyzing the thermodilution curve recorded most often in the femoral artery, using a specific thermistor-tipped catheter.[3]

For PWA, the PiCCO and VolumeView devices are based on the 3-element Windkessel model, which includes the characteristic impedance of the aorta, the arterial compliance, and the systemic vascular resistance. The devices analyze the geometry of the pressure curve recorded in the femoral artery. They also estimate the waveform of the pressure curve at the aortic level that differs from the peripheral pressure curve owing to the pulse wave amplification phenomenon, which itself depends on arterial resistance and compliance. Finally, they must make some assumptions to estimate arterial compliance, and measure CO.[4]

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The PiCCO device estimates CO by measuring the area under the systolic part of the arterial curve and dividing it by the aortic compliance. It also integrates some geometrical properties of the pressure curve. The arterial compliance is estimated by a proprietary algorithm at each time calibration is performed. Finally, the algorithm takes into account the systemic vascular resistance, which is continuously tracked by another algorithm. This allows the PiCCO device to obtain a starting value of CO, from which the monitor continuously reassesses CO by an algorithm taking into account the arterial pressure curve and the first derivative of pressure on time. Each time calibration is performed, the value of PWA-derived CO, which may drift over time, is reset to the value of CO provided by transpulmonary thermodilution. Overall, validation studies reported an acceptable reliability for the PiCCO pulse contour analysis CO.[3] The VolumeView device also calibrates PWA by transpulmonary thermodilution. The VolumeView-PWA algorithm, which is similar to the FloTrac (Edwards Lifesciences, Irvine, CA) (see Invasive Uncalibrated PWA Devices, below) and different from the PiCCO-PWA algorithm, has been validated in critically ill patients.[5]

Systems Calibrated by Lithium Dilution

The lithium dilution technique (LiDCOplus monitor; LiDCO Ltd, London, United Kingdom) consists in injecting a small amount of lithium chloride in a central vein and detecting the changes in lithium concentration in a radial artery. Using the Stewart–Hamilton principle, CO can be thus calculated. It has been demonstrated to be reliable compared with the pulmonary artery thermodilution.[6]

The PWA of the LiDCOplus is based on the principles of conservation of mass and power and not on a Windkessel model. Stroke volume is calculated from an analysis of the stroke volume–induced pulsatile change in the pressure waveform. In addition, arterial compliance is inferred from the patient's biometric data. The PWA is calibrated each time a lithium dilution is performed.

INVASIVE UNCALIBRATED PWA DEVICES

These devices provide a PWA-derived CO without any calibration. They do not require any specific sensor-tipped catheter and can be plugged to any arterial line.

With the FloTrac, the uncalibrated PWA estimates stroke volume as the product of pulsatility and a K factor. Pulsatility is estimated from the standard deviations of arterial pulse pressure measurements. K quantifies arterial compliance and resistance, and it is estimated from the patient's morphometric data, which are compared to a large database of pressure waveform recordings. K is automatically adapted every 60 seconds by taking into account some geometrical properties of the arterial pressure curve, such as skewness and kurtosis.

With the ProAQT (Pulsion Medical Systems, Feldkirchen, Germany), the starting value of CO is not estimated from the Windkessel model, but through an "auto-calibration" that uses the patient's biometric data, mean arterial pressure, and heart rate. After the initial auto-calibration, the ProAQT performs PWA with a method that is similar to that of the PiCCO system. An automatic "auto-calibration" of CO can also be performed at any time. PWA can also be "externally" calibrated with a value of CO manually entered and measured by another technique (eg, echocardiography) in the system.

With the LiDCOrapid (LiDCO Ltd, London, United Kingdom), the uncalibrated PWA uses the same algorithm than the LiDCOplus. It is possible to perform an external calibration with an independent CO measurement.

With the MostCare (Vygon Health, Padova, Italy), the noncalibrated PWA uses the "theory of perturbations." The estimation of CO is based on the area under the arterial pressure curve, on the analytical description of the arterial pressure waveform and on the instantaneous acceleration of the arterial vessel cross-sectional area.

The FloTrac and the ProAQT systems are considered reliable in the perioperative setting,[4,7] but not during liver transplantation surgery[8] and in patients with shock under vasopressors.[9,10] Indeed, if the vasomotor tone changes to a large extent, the estimation of the arterial compliance and resistance is unreliable[11] and these systems are no longer valid.[4,7]

NONINVASIVE UNCALIBRATED PWA DEVICES

With the volume clamp method (Clearsight; Edwards Lifesciences, Irvine, CA; and CNAP; CNSystems, Graz, Austria), an arterial pressure waveform is obtained noninvasively.[1,4] An inflatable cuff, which contains plethysmography sensors, is wrapped around a finger. The plethysmography sensors estimate the blood volume contained in the 2 finger arteries. The cuff constantly inflates and deflates to keep the volume of the arteries constant throughout the cardiac cycle. Arterial pressure is then estimated from the pressure measured inside the cuff. Although the reliability of CO trending measured by the Clearsight (ex-Nexfin; BMeye, Amsterdam, the Netherlands) was shown to be acceptable in the operating room setting,[12] its use is questionable in patients with shock, due to peripheral edema and vasoconstriction.[13]

With the radial artery applanation tonometry (T-Line; Tensys, San Diego, CA), the pressure waveform is continuously recorded by an electromechanically driven sensor located in a bracelet placed around the patient's wrist. The PWA uses a proprietary auto-calibrating algorithm. This technique needs to be further validated both in the perioperative and intensive care settings.[4]

HOW CAN THE PWA BE HELPFUL IN CLINICAL PRACTICE?

Continuous Monitoring of CO

The main interest of the PWA is to provide a beat-by-beat measurement of CO. This is useful for detecting short-term CO changes during surgery as well as for assessing the response of CO during dynamic tests of fluid responsiveness, such as end-expiratory occlusion and passive leg raising.[14]

Monitoring of Stroke Volume Variation

Since they perform a beat-by-beat estimation of stroke volume, the PWA devices automatically calculate and display the stroke volume variation (SVV), a dynamic marker of preload responsiveness.[14] The majority of the PWA devices also display the pulse pressure variation (PPV).[14] The PPV and SVV lose their value for predicting fluid responsiveness in many situations commonly encountered in the intensive

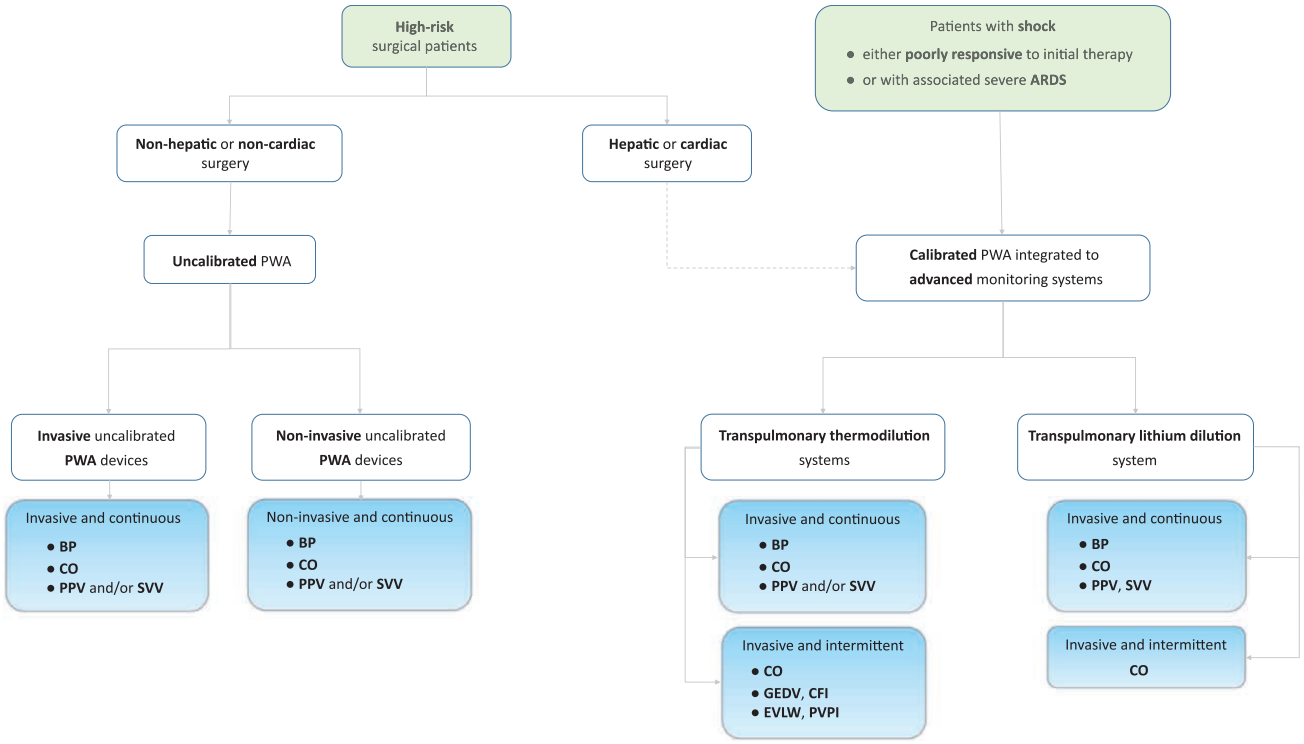

Figure. The place of pulse waveform analysis in high-risk surgical patients and in patients with shock. ARDS indicates acute respiratory distress syndrome; BP, blood pressure; CFI, cardiac function index; CO, cardiac output; EVLW, extravascular lung water; GEDV, global end-diastolic volume; PPV, pulse pressure variation; PVPI, pulmonary vascular permeability index; PWA, pressure waveform analysis; SVV, stroke volume variation.

care setting, the main ones being spontaneous breathing activity, cardiac arrhythmias, low tidal volume, and low lung compliance.[3] However, they can be useful in the perioperative context, where they are generally reliable. Their inclusion in goal-directed algorithms for the intraoperative fluid management was demonstrated to improve outcome in comparison with conventional management.[15]

WHEN SHOULD WE CHOOSE UNCALIBRATED DEVICES USING PWA FOR HEMODYNAMIC MONITORING?

In Surgical Patients

It is now recommended to use a perioperative hemodynamic monitoring in high-risk patients since it reduces mortality and morbidity.[1] This beneficial effect has been demonstrated with several CO monitoring devices including the ones using PWA. They are particularly suitable in this context, where the reliability of CO measurements and trending is considered acceptable[4,7] and where their low invasiveness is an indisputable advantage.[4] In addition, they can provide monitoring of SVV (or PPV), which is particularly reliable and useful in this setting. Nevertheless, the uncalibrated PWA cannot be used during surgical procedures able to induce changes in arterial tone,[10] for instance during liver transplantation surgery.[8] During cardiac surgery, the hemodynamic information provided by uncalibrated devices is insufficient and an advanced monitoring system is generally required (Figure).

In Critically Ill Patients

Monitoring CO should be used when the circulatory shock resists initial therapy.[2] Since uncalibrated PWA devices are unreliable,[4,9,11] advanced hemodynamic monitoring is recommended in this setting.[2,5] Calibrated PWA coupled to transpulmonary thermodilution is particularly adapted for this purpose. Not only does recalibration improve the reliability of CO estimation but also transpulmonary thermodilution provides other variables (Figure), such as extravascular lung water and pulmonary vascular permeability index.[3] These systems are appropriate for guiding fluid management of complex patients as they help to assess the benefits/risks ratio of fluid administration.[3] The expected benefits are assessed by markers of preload responsiveness (PPV, SVV, or the response of PWA-derived CO to end-expiratory occlusion or passive leg raising). The risks of fluid administration are assessed by extravascular lung water and pulmonary vascular permeability index.

CONCLUSIONS

The PWA provides a real-time and continuous measurement of CO and SVV. Devices that are calibrated with an independent technique measuring CO are more reliable than uncalibrated devices, especially in cases of changes in vascular tone. Nonetheless, the calibrated devices generally require a femoral artery catheter. The respective place of different devices has become clear, the uncalibrated systems being more suitable for the perioperative context while the calibrated devices are reserved for the most complex critically ill patients. Undoubtedly, technological refinements will make noninvasive PWA devices more reliable and increasingly used in the future, at least in the perioperative setting.

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