Cardiac Output Monitoring in the Post-PAC Era: Contour Analysis for Cardiac Output Determination

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Objectives:
• Describe the various methods of contour analysis for cardiac output measurement.
• Give assessments and perspectives of relative accuracy.
• Discuss limitations of these technologies.
• Discuss newer technologies.

Contour analysis is the derivation of additional information from the shape, amplitude, and features of a waveform. There are a number of systems that use contour analysis to estimate or calculate cardiac output. These systems take a waveform and attempt to derive additional information from it. The first of these systems use arterial pressure waveforms from the standard radial arterial pressure catheter while others use special femoral, brachial, or axillary arterial catheterization. There are a number of different mathematical models that are used to estimate cardiac output from the pressure waveform. The second main form of contour analysis uses Doppler ultrasound to attempt to calculate cardiac output. These systems use either a dedicated esophageal Doppler device measuring a signal from the descending aorta or a transesophageal echocardiography derived measurement looking at flow across the left ventricular outflow tract, mitral valve, or pulmonary artery. The final contour analysis systems use impedance signals from either surface impedance measurements or electrodes on the endotracheal tube (ECOM) which measure impedance from the ascending aorta to derive ascending aortic blood flow. Each of these systems will be discussed in the present lecture.

There are a number of issues that must be considered when evaluating contour analysis derived measures of cardiac output. The first is accuracy. The standard approach to measurement of the accuracy of a cardiac output device is to place the device in patients who would normally have a thermodilution cardiac output catheter placed as part of their routine care and then compare the “test” device to the pulmonary artery thermodilution cardiac output measurements. There are several issues with this type of experiment. The first is that thermodilution cardiac output measurements have error of +/- 20%. Despite being treated as a “gold” standard,
thermodilution cardiac output measurements are not perfect. In an analysis of 10,000 room temperature cardiac output measurements injected one minute apart, the correlation between a single thermodilution (TD) cardiac output measurement and the next one, was $R^2 = 0.50$, limit of agreement +/- 2.0 liters/minute. When 8,500 iced injections were compared, the correlation improves to $R^2 = 0.70$ and the limit of agreement is +/- 1.5 liters/minute. Thermodilution cardiac output measurements don’t correlate highly with themselves, when compared to other systems the error is the combination of the TD and “New” system error. Thermodilution cardiac output measurements need to be taken in large numbers and averaged. Single measurements mean almost nothing. The next important point is that 70% of all thermodilution cardiac output measurements during and after CABG are within +/- 20% of (cardiac index ) $CI = 2.0 \text{l/min/meter}^2$. If a device simply guesses a cardiac index of 2.0 liters/minute/meter$^2$, it will be correct 70% of the time. A stopped clock is only correct twice a day, a cardiac output device that simply reads $CI = 2.0$ is correct 70% of the time. There is very little true variation in cardiac outputs during CABG surgery and any error in a device must be added to the error of the pulmonary artery thermodilution system. It is impossible for a device to have an $R^2 = 1.0$ because the “gold standard” thermodilution isn’t perfect and any error of the device must be added to the error of the thermodilution measurements.

The next issue is what equation a device uses. There is a very simple relationship between cardiac output (CO), mean arterial pressure (MAP), central venous pressure (CVP), and systemic vascular resistance (SVR): $CO = (MAP-CVP)/SVR$. If mean arterial pressure, central venous pressure, and systemic vascular resistance, are known, it is possible calculate cardiac output. If SVR is unchanged, and CVP is guessed at, simply knowing the MAP is sufficient to get CO. The problem with this simple model is when SVR changes, the measurement of CO is incorrect. If CVP changes, CO is incorrect. In situations where it would be valuable to know the cardiac output, the SVR and CVP have probably changed, making calculation of CO incorrect. The other really important thing to remember is the equation $CO = SV \times HR$, where stroke volume (SV) and heart rate (HR) are related to cardiac output, should not be interpreted as a direct relationship between HR and CO. Raising HR may lower SV and have no effect on CO. It is true that $SV = CO/HR$. But it is not strictly true that $CO = SV \times HR$ where HR and SV are independent variables. When venous return is fixed, raising heart rate lowers stroke volume, leaving cardiac output unchanged.

Devices attempt to overcome these issues by making more complex mathematical models. They will attempt to model both the arterial resistance and compliance using a Windkessel Model. Windkessel is the German word for Wind Kettle which was a shock absorber filled with air used to absorb impulses in steam and water systems. In buildings with steam heating, windkessels are used to reduce impulses which lead to radiator noise and pipe damage. There are a number of windkessel models with either one resistor and one capacitor, or two resistors and a capacitor, or two resistors, a capacitor, and an inductor. Each system relies on guessing the values of the resistors and capacitors from the waveform shape. Once the value of the resistors and capacitors are established, the cardiac output necessary to cause the observed arterial pressure waveform can be derived. The problem with these systems is simply that they don’t really know the values of the resistors and capacitors, so they don’t really know the cardiac output. Moreover, resistance changes with time, reflexes, pressure, medications, disease state. Capacitance is more constant and less effected by reflexes or medications but is non-linear with
pressure. Any change in resistance or capacitance will make the estimation of cardiac output in error. No amount of complex math will overcome the simple fact that the parameters are non-linear, time-variant, and unknown.

Multiple cardiac output systems have attempted to overcome this fundamental problem by using a system of calibration. LiCO used a lithium as an indicator for lithium indicator dilution to calibrate the model.\textsuperscript{1} Lithium injections were performed once or twice a day to reduce the possibility of lithium toxicity. Unfortunately, resistance changes more frequently than once or twice a day. The PICCO system PICCO placed two catheters. One was a central venous catheter with a thermister. The second was a femoral, brachial, or axillary arterial pressure catheter and thermister. An injection using the central venous catheter of saline was used for standard thermodilution measurements with the temperature sensor in the arterial pressure catheter.\textsuperscript{2} The PICCO system required central venous catheterization with its attendant risks. It also required canulation of a major arterial vessel (femoral, brachial, or axillary) with increased risk over the radial artery. The PICCO system required frequent calibration when ever there was a clinical change.\textsuperscript{3} PICCO is not accurate without recalibration after any clinical change.\textsuperscript{2} The PICCO system is essentially a higher risk pulmonary artery thermodilution catheter because of the femoral artery catheterization, with lower accuracy than standard thermodilution. Correlations for PICCO range from $R^2 = 0.22\text{-}0.6$. PICCO is not acceptable in hemorrhage, sepsis, hemodynamic instability, or vasopresor administration.\textsuperscript{3,4} In situations where resistance is abnormal, it is inaccurate unless repeatedly recalibrated.\textsuperscript{3,4}

The Vigileo system attempts to use contour analysis in an uncalibrated system.\textsuperscript{5} Vigileo connects to an existing arterial catheter and performs continuous “self-calibration” through its automatic vascular tone adjustment and calculates flow parameters every 20 seconds. Vigileo “continuously monitors changes in patient’s vascular tone” (compliance and resistance). It is interesting that Edwards, which makes thermodilution catheters and continuous cardiac output monitors, did not use calibration from the PA catheter in the Vigileo system, but they did not. Vigileo, in an uncalibrated state, has poor correlations.\textsuperscript{5,6} Sakka et. al. Br J Anaesth 99:3 2007 found an $R^2 = 0.26$, Bias 1.54, Limit of Agreement 1.74.\textsuperscript{6}

Contour analysis can be used with esophageal Doppler systems to measure cardiac output. There are three forms of these devices. The first is a dedicated probe in the esophagus which images the descending aorta. It uses an algorithm based on age, height, and weight to estimate aortic area. It then calculates the velocity time integral (VTI) from flow in the aorta. The VTI is simply the area of the Doppler spectral waveform. The VTI is multiplied by the estimated aortic area to get the stroke volume (SV). $SV \times HR = CO$. The next system is slightly more complicated. It uses aortic imaging to actually measure the aortic area. It then multiplies the VTI times the aortic area measured by echo, to get the SV. And then uses: $SV \times HR = CO$. Both of these systems have the same fundamental problem. Descending aortic flow is NOT total cardiac output. If the ratio of flow in the great vessels to the rest of the body changes, the estimate of total cardiac output from descending aortic flow will be in error. There is also an error in the estimation or calculation of aortic area. The correlations for these esophageal Doppler cardiac output devices are OK but not great. There are a number of studies where fluid management is adjusted based on the esophageal Doppler measurement of cardiac output which
show improved clinical outcomes such as reduced length of stay.\textsuperscript{7-12} These devices should be commended for attempting to demonstrate clinical benefit from the device.\textsuperscript{7,12}

Transesophageal echocardiography (TEE) can be used to measure cardiac output across the pulmonary artery, mitral valve, or left ventricular outflow tract.\textsuperscript{13-15} The calculation requires measuring the conduit area using echo. It then requires measuring the velocity time interval (VTI). $SV = VTI \times \text{Area}$. CO = HR * SV. TEE derived measurement of cardiac output require experience with TEE and time to make the measurements and calculations. Images must be lined up with the Doppler signal.\textsuperscript{13} If the flow is at an angle to the Doppler signal, one must multiply by the cosine of the angle. Unfortunately, Cosine (90 degrees) = 0. Which means the Doppler signal must be lined up with the flow to be accurate. TEE derived measurement of cardiac output have correlations between 0.3 and 0.85.\textsuperscript{13,15}

Bioimpedance systems use contour analysis to measure cardiac output.\textsuperscript{16} Bioimpedance is the measurement of electrical voltage resulting from an alternating current applied to a structure. There are three Bioimpedance approaches. The first, surface bioimpedance, puts the electrodes on the neck and below the diaphragm. Surface bioimpedance is used to detect respiratory efforts on most ICU type monitors. When surface bioimpedance is used to attempt to calculate cardiac output, the correlations are extremely poor. The second type of system use a multi-electrode catheter placed in the ventricle.\textsuperscript{17} Commonly these systems use five electrode pairs and a 20 KHz sinusoidal signal. Left ventricular volume is calculated continuously. Millar pressure transducers combined with the impedance based volume conductance system, can be used to measure ventricular pressure-volume relationships, the end-systolic pressure-volume relationship, the diastolic pressure-volume relationship, and completely describe global ventricular function. These systems are complex to use and are restricted to research use. The ECOM (Endotracheal Cardiac Output Monitor) system was developed to attempt to make a simple system which would have the advantages of an internal impedance measurement like the volume conductance system, but without the risk of an intra-ventricular catheter. The ECOM system uses a three dimensional electrode array placed on the endotracheal tube balloon.\textsuperscript{18} The soft, smooth, flexible, electrodes are silver doped plastic sprayed on the ETT balloon. ECOM uses a 100 KHz sinusoidal 2 ma current and measures voltages in three dimensions from the ETT cuff. The endotracheal tube cuff, when placed in a standard position, is less than a centimeter from the ascending aorta or aortic arch. ECOM measures ascending aortic blood flow using electrical signals. Blood is an ionic solution. Current is passed by the ions. As blood is accelerated and decelerated in the aorta, the ionic velocity, which is close to the fluid velocity, is changed slightly. This change in ionic velocity, changes electrical resistance slightly, which changes the voltage, which allows detection and measurement of aortic blood flow.

The ECOM system has been studied in more than 500 patient undergoing cardiac surgery and many chronically instrumented pigs. ECOM cardiac output measurements correlate with thermodilution cardiac output measurements with $R^2 = 0.63$, Slope = 0.90, Intercept 0.14 liters/minute, Limit of Agreement -2.3 to 1.7 liters/minute, Bias = -0.31 liters/minute ECOM cardiac output measurements correlate with thermodilution cardiac output measurements with $R^2 = 0.63$, Slope = 0.90, Intercept 0.14 liters/minute, Limit of Agreement -2.3 to 1.7 liters/minute, Bias = -0.31 liters/minute. The latest 101 patient study of ECOM enrolled adults patients undergoing all forms of cardiac surgery including CABG, off and on pump, aortic valve repair, aortic arch repair, robotic surgery, and mitral valve surgery.
In summary Cardiac Output Monitoring in the Post-PAC Era has multiple forms of Contour Analysis for Cardiac Output Determination. Measuring cardiac output is a difficult problem. There are multiple systems which have mixed functionality and accuracy. The uncalibrated arterial pressure based cardiac output monitors, such as Vigileo are not accurate and loose accuracy when either resistance or compliance vary. Calibrated contour based systems calculate R and C, but require recalibration whenever clinical situation changes. With a recalibration necessary every time something changes, the true system is the calibration system, not the contour analysis system. Why bother with a system that is simply a thermodilution catheter extender? Esophageal Doppler systems have attempted to show clinical benefit and the other cardiac output systems must follow in this trend to show clinical benefits, not simply accuracy against thermodilution. The Endotrachal Cardiac Output System (ECOM) uses an impedance based system from an endotracheal tube. It does not require recalibration necessary every time something changes, the true system is the calibration system, not the contour analysis system. Why bother with a system that is simply a thermodilution catheter extender? Esophageal Doppler takes some skill and has limited accuracy. It’s main limitation is simply that descending aortic blood flow is NOT total cardiac output. Continuously adjusting the descending aortic probe takes effort. Esophageal Doppler systems have attempted to show clinical benefit and the other cardiac output systems must follow in this trend to show clinical benefits, not simply accuracy against thermodilution. The Endotrachal Cardiac Output System (ECOM) uses an impedance based system from an endotracheal tube. It does not require calibration, does not require positioning, works while TEE is in place, and has reasonable accuracy that is superior to the arterial pressure contour analysis systems.

References:

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