

Esophageal Doppler: Noninvasive Cardiac Output Monitor

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In this article we describe the esophageal Doppler, a noninvasive, instantaneous cardiac output monitor. Its reliability has been demonstrated to be comparable to that of other current techniques used in the clinical arena to measure cardiac output. It helps guiding intravascular fluid resuscitation by quantifying the increase in flow in response to fluid challenges and by indicating the plateau of the patient's cardiac function curve. When the plateau has been reached, further fluid loading may result in congestion without improvement in systemic flow. Thus, measuring cardiac output is the only way to determine the upper limit for fluid intake. In addition, a strategy based on cardiac output optimization has proven beneficial in high-risk surgical patients. (ECHOCARDIOGRAPHY, Volume 20, November 2003)

ultrasound imaging, cardiac function, transesophageal echocardiography

Echocardiography in conjunction with different Doppler modalities is a powerful diagnostic tool that can be used at bedside in the intensive care unit (ICU) or in the operating room to clarify the mechanism of unstable hemodynamic situations. Studies and reports have emphasized the superiority of echocardiography above the classic pulmonary artery catheterization for both diagnostic accuracy and speed.¹⁻³ The noninvasive character of ultrasound that allows serial measurements prompted several authors to use echocardiography for monitoring in selected patients. They suggested that echocardiography could be useful to monitor cardiac function (regional and global) and cardiac preload using left ventricular short-axis area.⁴⁻⁸ However, echocardiography lacks many features of the ideal monitoring device. Its major flaws are the need for a trained operator and a relatively high cost per machine and per procedure.

Esophageal Doppler, another ultrasound-based technique, seems more suited for long-term hemodynamic monitoring. Introduced in the early 1970s,^{9,10} this technique allows noninvasive measurement of instantaneous blood flow velocity in the descending aorta, from

which stroke volume and cardiac output can be calculated with reasonable reliability. Learning this technique requires less training than regular echocardiography or pulmonary artery catheterization. It is also noninvasive in sedated patients, making serial measurements easy to perform.

This study will discuss the pertinence of stroke volume (or cardiac output) monitoring, the principle of stroke volume estimation using esophageal Doppler, the validation of the technique, and the potential benefits of hemodynamic optimization in high-risk surgical patients.

Why Is It Important to Monitor Stroke Volume and Cardiac Output?

One of the central concerns of anesthesiologists and intensivists involved with perioperative resuscitation or critical care is to maintain adequate organ perfusion. Adequate perfusion means sufficient pressure to maintain vessel lumen patent at all times, and sufficient flow to deliver the appropriate amount of oxygen and metabolites to every cell, and to clear the byproducts of metabolism such as carbon dioxide, lactate, H⁺ ions, etc. In many instances, pressure is the only aspect of perfusion that is carefully monitored, whereas flow is simply ignored. The main reason for disregarding flow monitoring is related to the difficulties encountered in obtaining flow measurements

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in patients. The thermodilution technique using a pulmonary artery catheter is not used on a routine basis due to relative complexity and potential side effects.¹¹ However, pressure measurements alone may not be sufficient. Because pressure is narrowly regulated by neurohumoral mechanisms, the same level of pressure may correspond to different flow states.

Measuring flow (cardiac output/stroke volume) is useful mainly for two reasons. First, flow is a sensitive indicator of the global cardiovascular performance. A reduction in stroke volume or cardiac output is evidence of some alteration in the cardiovascular system: either a reduction in venous return (hypovolemia or vasoplegia), or an alteration in cardiac function (right or left heart). Therefore, monitoring cardiac output can be an early warning, albeit nonspecific, of any circulatory disturbance. The second reason to measure flow is that it allows the assessment of fluid responsiveness (or preload dependence) of the cardiovascular system, i.e., its ability to increase flow in response

to a fluid challenge. This is helpful in titrating fluids (incremental fluid loading) to “optimize” cardiac output up to its maximal value, which has proven a good strategy in selected surgical patients.

Esophageal Doppler

Methods

The esophageal Doppler technique is based on the measurement of blood flow velocity in the descending aorta by means of a Doppler transducer (4-MHz continuous or 5-MHz pulsed wave, depending on manufacturer) placed at the tip of a flexible probe. The probe can be introduced orally in anesthetized, mechanically ventilated patients. Following oral introduction, the probe is advanced gently until its tip is located approximately at the mid-thoracic level, and then rotated so that the transducer faces the aorta and a characteristic aortic velocity signal is obtained (Fig. 1). Probe position is

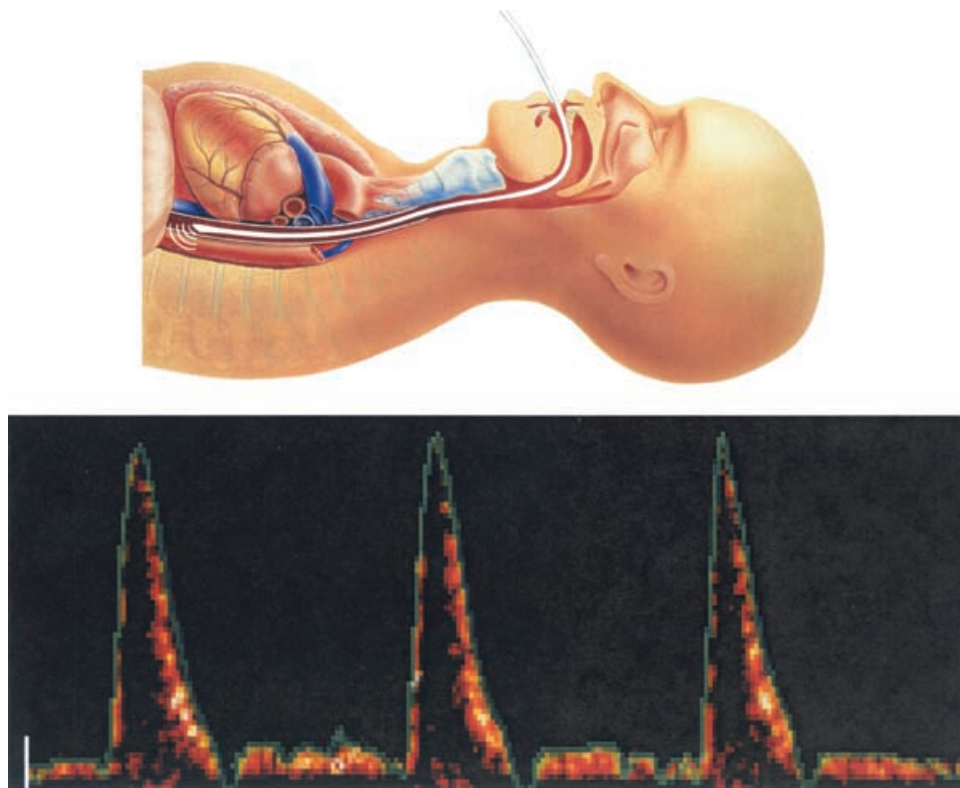


Figure 1. (Top panel) Schematic representation of esophageal Doppler probe in a patient demonstrating the close relation between esophagus and descending thoracic aorta. (Bottom panel) Characteristic velocity waveform obtained in the descending aorta. The spectral representation illustrates that most red blood cells (orange-white color) are moving at the maximum velocity (close to the green envelope) during systole, and that diastolic flow is minimal.

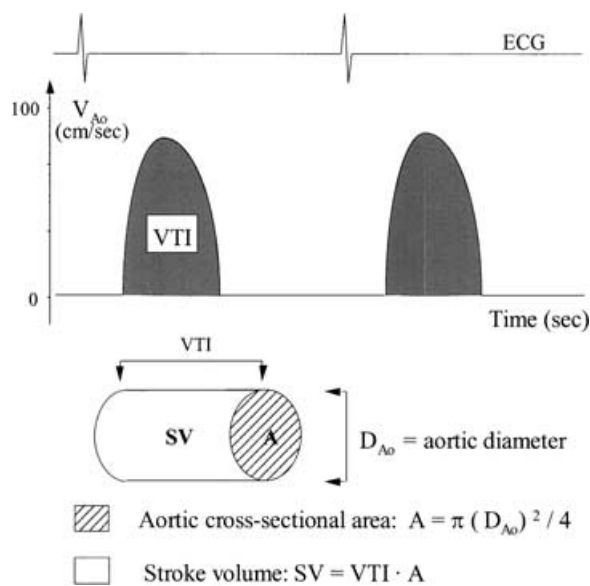


Figure 2. Principle of stroke volume calculation from aortic velocity (V_{Ao}) measurements. The area under the maximum aortic velocity envelope (VTI) is calculated as a velocity time integral (in $\text{cm/sec} \cdot \text{sec} = \text{cm}$) and represents the stroke distance. Assuming that all red blood cells are moving at maximum velocity and that aortic cross-sectional area (A) is constant during systole, stroke volume (SV) is obtained by multiplying stroke distance (VTI) by the aortic cross-sectional area A .

optimized by slow rotation in the long axis and alteration of the depth of insertion to generate a clear signal with highest possible peak velocity. Gain setting is adjusted to obtain the best outline of the aortic velocity waveform, and a high-pass filter eliminates the noise related to low-frequency vessel wall motion.

The measurement of stroke volume using esophageal Doppler is derived from the well established principles of stroke volume measurement in the left ventricular outflow tract using transthoracic Doppler echocardiography (Fig. 2).¹² Several assumptions are required to transpose what has been validated in the left ventricular outflow tract to the descending aorta: (1) an accurate measurement of the velocity of the descending aortic blood flow; (2) a “flat” velocity profile throughout the descending aorta; (3) an estimated aortic cross-sectional area close to the mean value measured during systole; (4) a negligible diastolic flow; and (5) a constant division of blood flow between the descending aorta (70%), and the brachiocephalic and coronary arteries (30%). The accuracy of velocity measurement requires good alignment

between the Doppler beam and the direction of blood flow, as well as knowledge of the angle at which the blood flow is insonated. Alignment is best assessed subjectively by optimizing the quality of the obtained signal based on the visual display of instantaneous velocity waveform and the Doppler sound.

The angle between the Doppler beam and blood flow is roughly the same as that between the transducer and the probe (45 or 60 degrees), because the esophagus and aorta are usually parallel in the thorax. This latter assumption may be correct in young, healthy patients, but is probably erroneous in elderly patients with scoliosis. Any discrepancy between estimated and real angles results in errors in calculated blood velocity. The larger the angle between Doppler beam and blood flow, the greater the inaccuracy in velocity measurement, as a consequence of inappropriate cosine in the Doppler equation.¹³ A “flat” velocity profile implies that all red blood cells move at the same speed through the vessel. In fact, the flow velocity profile in the descending thoracic aorta is rather parabolic than flat¹⁴ (i.e., the red blood cells at the center of the vessel move faster than those at the periphery). Hence, the use of the maximum velocity envelope to compute stroke distance may result in overestimation of stroke volume.

Beside measurement of the cross-sectional area of the descending aorta can be performed by using transesophageal echocardiography, however, this technique is operator dependent and not available everywhere. The manufacturers of esophageal Doppler have solved this problem either by incorporating an M-mode echo transducer into their probe to measure instantaneous aortic diameter (HemoSonic; Arrow International, Reading, PA), or by providing a nomogram to estimate the cross-sectional area of the descending aorta based on the patient’s age, weight, and height (CardioQ [Deltex Medical, Chichester, United Kingdom]; Waki [Atys Medical, Soucieu-en-Jarrest, France]). Systematic errors due to a discrepancy between the actual area and the nomogram value would not affect the trend of cardiac output variation with time.¹⁵ However, a large variation in cardiac output can be underestimated by not taking into account the concomitant change in the aortic diameter that is necessarily in the same direction. Finally, some manufacturers of esophageal Doppler choose to provide systemic cardiac output rather than descending aortic blood flow. They calculate the systemic values by assuming a constant partition

of blood between cephalic (30%) and caudal (70%) territories. Although relevant in healthy, resting patients, this partition may vary according to hemodynamic conditions, reflex activation, or metabolic activity within different organs. Therefore, the assigned constant ratio of 70% to 30% may become inaccurate under a variety of pathophysiologic conditions.¹⁵⁻¹⁷

Learning Curve and Reproducibility

Esophageal Doppler is a simple technique and most users acknowledge that it is fairly easy to achieve adequate probe positioning and obtain reproducible results.^{18,19} Authors studying the learning curve of the technique noted a dramatic improvement in the skills of untrained operators after performing only 10 or 12 probe placements.^{20,21} Interobserver variability has been reported to be less than 10%, while intraobserver variability is only 8%, a figure that is closer to 12% for thermodilution.^{15,18,22,23} Probe displacement can occur during prolonged monitoring as a result of various causes (nursing procedures, deglutition, gravity, etc.), and results in a poorly defined velocity envelope or a loss of signal. It is mandatory to ensure an adequate signal prior to interpreting Doppler-derived data. Failure to reposition the probe prior to each measurement may lead to grossly erroneous cardiac output values.

Validation of Cardiac Output Measurement

“Gold standard” techniques for cardiac output measurement, such as aortic electromagnetic or ultrasound transit time flowmeters, are highly invasive and cannot be used in patients. Clinically available techniques include Fick principle, dye dilution, thermodilution, and transthoracic echo-Doppler. These techniques are less accurate and reproducible and none of them has ever been validated in comparison to a gold standard in critically ill, mechanically ventilated patients. The widespread use of thermodilution in ICUs has made it a “reference” technique, despite its well-known pitfalls.²⁴ Therefore, all trials aimed at validating cardiac output measurements using esophageal Doppler have compared it with thermodilution. These studies generally found a rather poor agreement between the two techniques, but suggested that the variations in cardiac output were tracked similarly.^{15,18,20,22,25}

More recently, a multicenter study compared multiple techniques and esophageal Doppler.²³ Patients from three different ICUs under-

went paired cardiac output measurements using thermodilution and esophageal Doppler. In addition, simultaneous suprasternal Doppler and indirect calorimetry based on Fick principle were used to measure cardiac output in some patients from one center. A good correlation was found between thermodilution and esophageal Doppler ($R = 0.95$), with a small systematic underestimation (bias = 0.24 L/min) using esophageal Doppler. The limits of agreement between thermodilution and esophageal Doppler were ± 1.8 L/min. Variations in cardiac output between two consecutive measures using either esophageal Doppler or thermodilution techniques were similar in both direction and magnitude (bias 0 L/min; limits of agreement ± 1.7 L/min; Fig. 3). Suprasternal

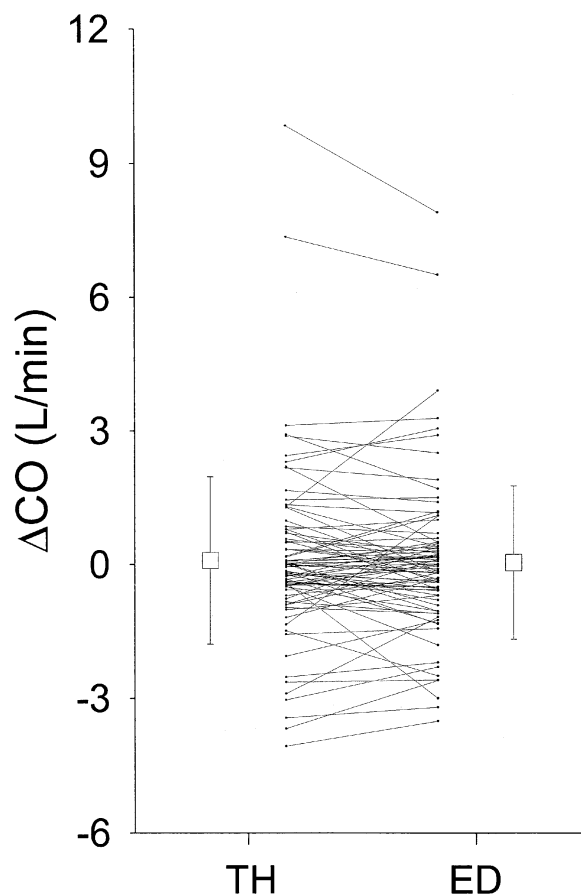


Figure 3. Eighty-eight paired measurements of cardiac output variations between two time points obtained simultaneously using thermodilution (TH) with a pulmonary artery catheter and esophageal Doppler (ED). Ideal agreement is represented by a horizontal line. Contradictory information with the two techniques was observed in only three patients.²³

Doppler and indirect calorimetry yielded similar correlations and agreements in the subset of patients in whom they were used. These results confirmed that esophageal Doppler can provide a noninvasive, clinically meaningful estimate of cardiac output and detect hemodynamic changes in mechanically ventilated, critically ill patients.

Hemodynamic Optimization in High-Risk Surgical Patients

Numerous studies have tested the hypothesis that improving tissue perfusion could improve the outcome of high-risk surgical patients.²⁶⁻⁴¹ Most of these studies used various combinations of fluids, vasodilators, and inotropes to achieve a measurable increase in oxygen transport. Using such therapeutic regimens it was possible to demonstrate a reduction

in mortality.^{26,27,29-31,40} or at least a decrease in postoperative adverse events and/or hospital stay.^{28,32,35,37,41} The four studies that used esophageal Doppler to monitor cardiac output improvement used only fluids (and no pharmaceutical agents) to increase tissue perfusion and demonstrated a reduction in postoperative morbidity.^{32,35,39,41} Esophageal Doppler was used as a mean of titrating the fluids and assessing the increase in cardiac output resulting from each fluid challenge (Fig. 4). Failure to increase cardiac output after a fluid challenge attests that the patient operates on the flat portion of the cardiac function curve and that further loading might result in venous congestion and not in perfusion improvement (Fig. 5). Hence, esophageal Doppler can also help in determining the upper limit for fluid-filling in every patient and reduce the risk of postoperative pulmonary edema.

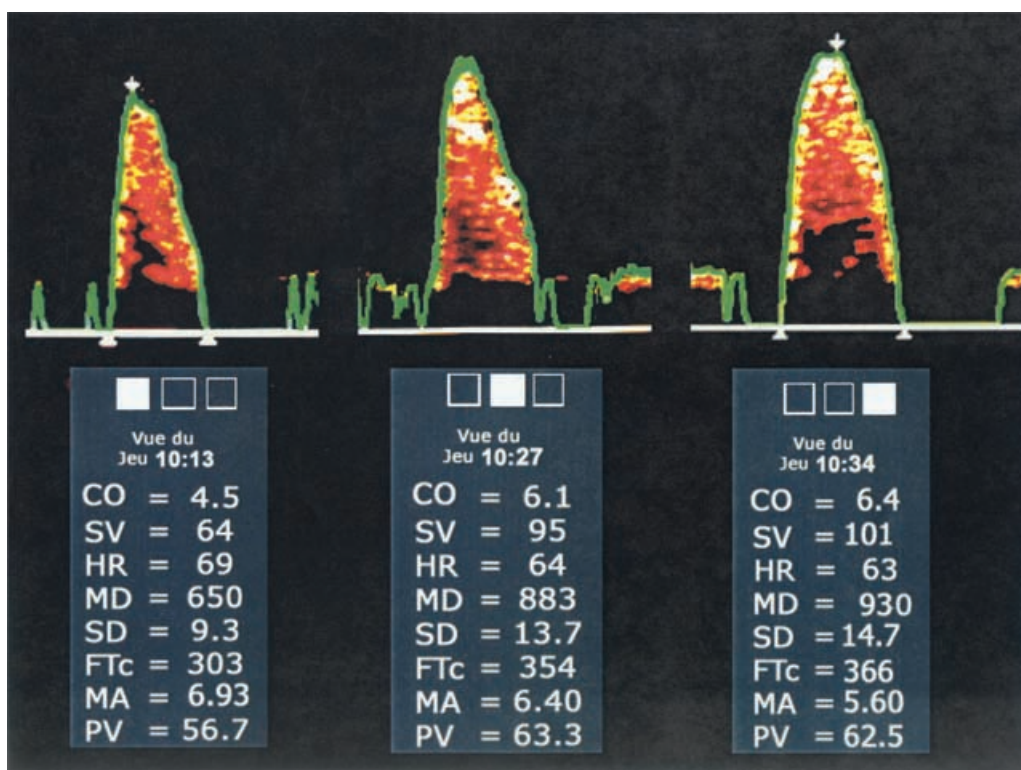


Figure 4. Representative example of the information obtained using esophageal Doppler monitoring during a fluid challenge (gelatin, 250 mL × 2) in a 61-year-old patient who underwent an operation for femoral neck fracture. The left panel illustrates baseline descending aortic velocity spectrum and values for cardiac output (CO), stroke volume (SV), and heart rate (HR). After the first fluid challenge (middle panel), CO and SV increased by 36% and 48%, respectively, while systemic arterial pressure and heart rate remained unaltered. After the second fluid challenge (right panel), CO and SV increased by 5%, without change in pressure and heart rate. The dramatic change in systemic perfusion was not reflected by pressure and heart rate monitoring alone.

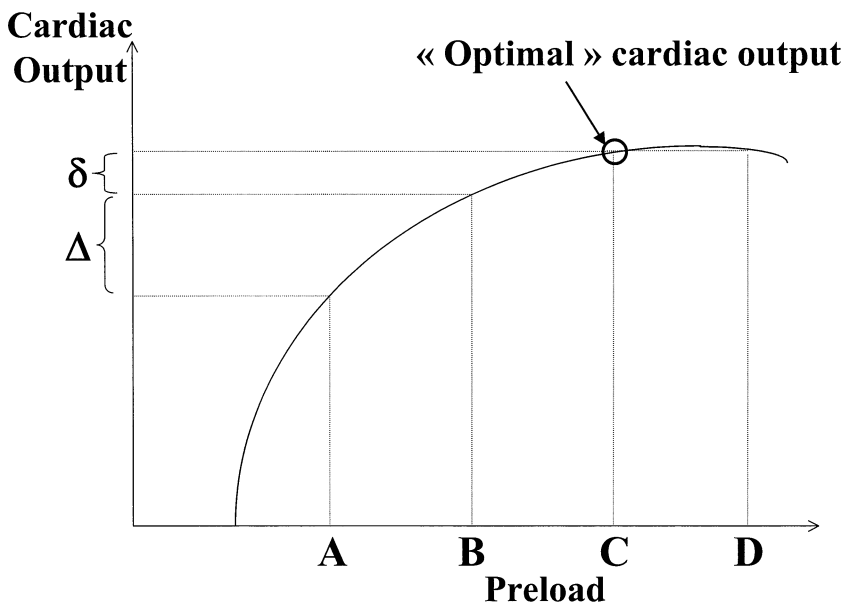


Figure 5. Cardiac function (Starling's) curve illustrating the effects of successive fluid challenges on cardiac output. The first increase in preload (from A to B) results in a large increase in cardiac output (Δ); the cardiovascular system operates in the "preload dependant" portion of the curve. The second increase in preload (from B to C) only results in a small increase in cardiac output (δ), and further loading (from C to D) does not yield any increase in cardiac output at all because the cardiovascular system is no longer preload dependant. Dynamic testing of the cardiovascular system using fluid challenges and flow monitoring allows definition of the "optimal" (maximal) cardiac output for an individual patient and avoids excessive fluid loading.

If optimization of cardiac output has demonstrated clinical benefits in high-risk surgical patients, it failed to do so in ICU patients.⁴²⁻⁴⁴ Although the exact reason for this difference remains unclear, it appears that "long-term" (ICU) optimization does not reproduce the beneficial effects observed in the "acute" perioperative setting. One exception to be mentioned is the recent study by Rivers et al.⁴⁵ that tested oxygen delivery optimization within 6-hours after onset of septic shock and found a reduction in mortality. In this study, quite similar to what was done in high-risk surgical patients, optimization was attempted at the very early phase of the disease when some potential damage might still be prevented by improved perfusion.

Conclusion

Cardiac output monitoring is undoubtedly very useful for the management of critically ill patients, especially its variations with patient's illness or resulting from therapeutic interventions. Esophageal Doppler offers several important advantages over other techniques. In addition to being minimally invasive in sedated patients, it requires minimal training and offers instantaneous rather than average cardiac output per minute.

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