Newer trends in monitoring: The esophageal Doppler monitor

KAREN E. KAUFFMAN, CRNA, MSN
Statesville, North Carolina
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The esophageal Doppler monitor is a recent development in hemodynamic monitoring that is used for surgical patients. It is relatively noninvasive and measures descending aortic blood flow by the Doppler effect. A comparison of this new monitor with the pulmonary artery catheter is cited numerous times throughout the literature and overall correlates well. Studies of the esophageal Doppler monitor show it to be a safe addition to operating room monitors for use by the anesthetist.

Key words: Esophageal Doppler, hemodynamics, monitoring, ultrasound.

Introduction

A great deal of research has been performed on the esophageal Doppler monitor, a new monitor for the operating room, as well as other critical care environments. British researchers have performed a considerable amount of study on this monitor. Doppler measurement of aortic blood flow is unique because rather than pressures, it relies on flow for assessment of circulatory function. The 2 primary approaches for aortic blood flow measurements are suprasternal and esophageal.

History of the Doppler principle

Christian Johann Doppler, an Austrian physicist and mathematician, described the Doppler effect in 1842. The Doppler effect has been defined as the apparent variation in frequency of any emitted wave, such as a wave of light or sound, as the source of the wave approaches or moves away, relative to an observer. Furthermore, if a source of sound is moving toward an observer, the effect seems higher in pitch, whereas if the source is moving away the effect seems lower. This concept is exemplified by imagining a train approaching an observer blowing a whistle. As the train moves closer to the observer the whistle’s volume becomes louder. The Doppler effect also is used in police radar systems to measure the speed of motor vehicles.

Various components of the Doppler effect differ when applied to the human body. For instance, the whistle sound frequency is traveling through a medium of air, whereas the moving blood cells are traveling through a medium of body tissue. The ultrasound beam is considered the “observer” in Doppler measurement of blood flow. The ultrasonic beam emits a frequency toward moving red blood cells, and part of the frequency is reflected back. The direction of the blood flow also can be determined using the Doppler effect by a positive or a negative frequency shift. If the blood is moving away from the
observer (transducer), then the distance between the reflected waves becomes longer, producing a lower frequency and a negative frequency shift.

The Doppler equation explains the aforementioned concepts and is rearranged to account for measurement of blood flow velocity.

\[ V = \frac{c f_d}{2 f_t \cos \theta}, \]

where \( V \) = flow velocity, \( c \) = speed of sound (1,540 m/s in body tissue), \( f_d \) = frequency shift (Hz), \( \cos \theta \) = cosine of angle between sound beam axis and velocity vector, and \( f_t \) = frequency of transmitted ultrasound (Hz). \(^{24}\) The 2 constants in this equation are the speed of sound and the frequency of transmitted ultrasound. Thus, it can be inferred that the velocity measured is dependent on the frequency shift and the cosine of angle between sound beam axis (Doppler transducer) and velocity vector (blood flow). \(^4\)

The 2 types of ultrasound waves are continuous and pulsed. A continuous wave uses 2 crystal transducers. \(^{24}\) One crystal transducer is piezoelectric and emits a continuous pure tone frequency ultrasound. Piezoelectric is a characteristic of crystals that can convert between mechanical and electrical energy. An electric potential applied to a piezoelectric crystal causes a small change in the shape of the crystal. Physical pressure applied to the crystal creates an electrical potential difference between the surfaces of the crystal by displacement of ions causing electric polarization of the crystal’s structural units. The other crystal is adjacent to the piezoelectric crystal and detects the reflected Doppler frequency shifts. \(^3\) This type of Doppler is particularly useful for measuring high-velocity blood flow, such as aortic blood flow. \(^3\)

The second type of ultrasound wave is called the pulsed-wave Doppler. This uses only 1 crystal that functions as an emitter and as a receiver. It detects the reflected Doppler frequency shifts in the time between the pulse of waves that it emits. \(^3\) This type of Doppler is especially useful for detecting signals of a specific location, whereas the continuous wave Doppler only has the ability to detect signals nonspecifically. For example, the continuous-wave Doppler can detect signals coming from the heart, intrathoracic veins, and the aorta, thus making it nonspecific. However, a skilled observer can easily differentiate the waveforms produced.

The uses of Doppler ultrasound technology have had medical applications since the 1970s. \(^2\) The various anatomic areas for which it is used range from intracranial to intrauterine. A transcranial Doppler measures the blood flow velocities of the middle and anterior cerebral arteries. The Doppler effect is further used in combination with 2-dimensional imaging in transesophageal echocardiography. \(^4\) It has uses in neonatal and obstetrical areas as well. More specific to the field of anesthesia, it has been used to detect venous air embolisms and, more recently, to estimate cardiac output. The 2 approaches for aortic blood flow Doppler estimation of cardiac output are supra-sternal and esophageal. The latter approach is the focus of the present review.

The suprasternal Doppler is a completely noninvasive monitor of cardiac output. \(^2\) This Doppler obtains information about ascending aortic blood flow transcutaneously at the suprasternal notch. From research in the 1960s and 1970s, it was determined that cardiac output could be estimated by the velocity-time waveforms produced by the Doppler frequency shifts. The area under the waveform is the distance a column of blood flows in the aorta, or the “stroke distance.” The stroke distance multiplied by the heart rate results in the minute distance, a linear measure of cardiac output. Knowledge of the aortic diameter and the stroke distance allows stroke volume to be calculated. By using the suprasternal Doppler approach to cardiac output monitoring, the aortic cross-sectional area was calculated by echocardiography.

The advantages of this approach to Doppler measurement of aortic blood flow are the properties of complete noninvasiveness, ease of access, and painlessness. \(^5\) The disadvantages of this system include the variation of signals between different observers, discontinuous monitoring, and anatomic and pathological variants making it difficult to obtain a good aortic signal.

The first description of the esophageal probe appeared in 1971 and purported to measure the aortic blood flow velocity as well. \(^2\) Throughout the course of the research on this approach, several variations of the probe characteristics were made. The size of the probe has been altered as have the external characteristics, such as a latex balloon for fixation. Continuous and pulsed-wave systems also were explored. Other attempts at perfecting this monitor included changing the frequency of the emitted wave, changing the angle of insonation (exposure to ultrasonic waves), and using echocardiography or a nomogram in estimating aortic diameter. The current esophageal Doppler monitor includes a 6-mm probe, a nomogram, an online, beat-by-beat monitor of stroke volume, and a 4-MHz, continuous-wave ultrasound frequency.

To use this monitor, age, height, and weight data are entered into the computer. The probe is
inserted into the esophagus until the notch (on the probe) is at the level of the patient’s teeth (which is approximately 35-40 cm beyond the teeth). Once inserted, the probe is connected to the monitor and rotated to obtain the best aortic signal. Qualified users will readily be able to ascertain that the probe is in correct position (see Figures 1 and 2 for representation of monitor and probe placement).

**Shape of the waveform**

An understanding of the waveform shapes produced by the aortic blood flow by Doppler measurement was present when this monitor was introduced. In the 1960s, researchers used implanted flowmeters and pressure cannulas, called electromagnetic flowmetry, to provide information on left ventricular performance. Several aortic indices were altered, such as posture, exercise, ischemia, hypovolemia, hypervolemia, and inotropic effects of the heart. The results of this work indicated that assessment of left ventricular function was possible through observing changes in accelerations and peak velocity in the waveforms produced.

Further studies of waveform shape were performed using the suprasternal Doppler. This resulted in a more extended knowledge base of peak velocity and acceleration in addition to flow time. Acceleration was termed mean or maximum. Mean acceleration describes the gradient of the upstroke of the waveform, and maximum acceleration describes the beginning of systole (and the waveform). Flow time and cycle time also were accounted for because it was learned that heart rate needs to be constant. Hemodynamic interventions affect heart rate, and the heart rate affects flow time. To make the heart rate constant, the flow time was corrected for heart rate by dividing it by the square root of cycle time (the Bazett equation).

Singer reviewed the summation of the research that used the suprasternal Doppler to ascertain waveform shape changes. Acceleration and peak velocity were noted to reflect inotropic changes accurately, while the corrected flow time reflected changes in systemic vascular resistance. In 1991, Singer et al reported their study of waveform changes in healthy subjects using the suprasternal Doppler. They gave inotropic and “afterload” drugs and removed the subjects’ plasma. Again, the peak velocity and acceleration accurately measured inotropic changes, and changes in “preload” and afterload were found by observing the corrected flow time.

The aforementioned research can be applied to the esophageal Doppler monitor in measuring descending aortic blood flow. Normal, age-appropriate ranges for peak velocity and mean acceleration also are provided through study of these age groups. The peak velocity range for a 20-year-old is 90 to 120 cm/s; for a 50-year-old, 70-100 cm/s; and
for a 70-year-old, 50 to 80 cm/s. Anything outside these ranges indicates hyperdynamic or hypodynamic circulation. The normal corrected flow time (FT\textsubscript{c}) is 330 to 360 milliseconds for all age ranges. Anything less than 330 milliseconds indicates hypovolemia or a vasoconstricted state, and anything more than 360 milliseconds indicates vasodilation. Peak velocity is narrower in hypovolemic states and decreased in amplitude with vasoconstriction.

Singer et al\textsuperscript{6} compared the changes in the hemodynamic status of subjects with simultaneous measurements from the pulmonary artery catheter (PAC). They noted that FT\textsubscript{c} and wedge pressure both increased with fluid challenges. However, the opposite is not true because the wedge pressure decreased with preload decreases, and the FT\textsubscript{c} increased until the preload decreased to a certain point in hypovolemia. It also was noted that in 1 subject with mitral stenosis, the wedge pressure was increased, whereas the esophageal Doppler depicted an underfilled left ventricle with a narrow peaked waveform. Figure 3 provides an example of waveforms that vary with different hemodynamic states.

![Figure 3. Changes in waveform shape following inotropic, preload, and afterload maneuvers\textsuperscript{2}](image)

**Esophageal Doppler monitor in the intensive care unit**

Most of the work performed with the most recently developed esophageal Doppler monitor occurred during the 1990s. The research has been performed in a variety of settings, including the intensive care unit (ICU), the operating room, and a combination of other settings. Alterations in hemodynamics result from positive-pressure ventilation with critically ill or surgical patients. Knowledge of the cardiac output, for example, is helpful for guiding therapeutic measures to optimize provision of oxygen to tissues. In 1989, Singer and Bennett\textsuperscript{7} reported their study of the effects of positive end-expiratory pressure (PEEP) on 10 patients in ICU who were being mechanically ventilated for treatment of acute respiratory failure.\textsuperscript{7} The authors increased the amount of PEEP and measured the cardiac output using the esophageal Doppler monitor and thermodilution (when present) with each change. They concluded that the cardiac output decreased with increases in PEEP and decreased further when coupled with left ventricular failure. Furthermore, this study\textsuperscript{7} showed that the esophageal Doppler monitor was a useful adjunct to monitoring cardiac output.

Patel and Singer\textsuperscript{8} performed another study of PEEP in mechanical ventilation and showed that the most desirable time to measure cardiac output was 15 minutes after changes in PEEP were made. It was at this point that no further changes occurred in the 10 patients studied, and 15 minutes was the minimal interval between PEEP changes and measurement of cardiac output to determine the need for hemodynamic intervention. Another study in 1994 examined the effects of manual hyperinflation of the lungs and subsequent hemodynamic changes using cardiac output.\textsuperscript{9} The resulting evidence supported the usefulness and accuracy of the esophageal Doppler to assess cardiac output changes, in addition to noting that changes occur as a result of tidal volume rather than pressure.

Other ICU-related studies were conducted comparing the thermodilution and esophageal Doppler techniques. The studies included patients who were mechanically ventilated, required a PAC, or both in the ICU setting.\textsuperscript{10-12} The outcomes all indicated that the esophageal Doppler monitor correlated well with the thermodilution technique but required a trained clinical operator. Furthermore, a good correlation between the Fick method and the esophageal method of measuring cardiac output has been noted.\textsuperscript{11,13}

**The use of the esophageal Doppler monitor perioperatively to reduce morbidity and mortality**

The use of anesthetics by skilled nurse anesthetists and anesthesiologists requires the use of critical monitors to guide their choices. As previously discussed, the use of pressure measurements is the mainstay of their monitoring choices in the
operating room. Furthermore, the use of the PAC is limited to patients who are critically ill or undergoing major surgery. Thus, much research of the esophageal Doppler monitor was and is still being performed in the operating arena as a noninvasive alternative or adjunct to the PAC.

In 1995, a study of postoperative morbidity and mortality was reported in Great Britain. Upon discovering reports of postoperative mortality between the years 1991 and 1992, the authors noted that more deaths occurred after elective than after emergency or urgent procedures, which sparked a number of studies. Also, during this study of the perioperative deaths, Sinclair and Singer noted that the major cause of morbidity and mortality in that time period was inadequate hemodynamic monitoring and fluid replacement.

This finding initiated an attempt to find a minimally invasive system to facilitate fluid resuscitation in the surgical patient. Sinclair et al. studied 40 patients undergoing surgery to treat a fractured neck of the femur and gave half of the patients the standard fluid therapy and the other half additional fluid challenges, guided by stroke volume and FTc. The aggressive fluid regimen improved outcome by a 40% reduction in hospital stay. A repeated study found that intraoperative intravascular volume loading to optimal stroke volume improved postoperative recovery, as shown by such evidence as a decreased length of hospital stay.

Other studies were conducted to attempt improving the postoperative outcome for surgical patients by using the esophageal Doppler monitor in conjunction with the gastric tonometer to measure gastric mucosal pH (pHi). It was already concluded that an abnormally low pH was associated with significant morbidity and mortality in surgical and ICU patients. The proposed explanation of this is that gastrointestinal mucosal pH may serve as a sentinel marker of tissue hypoperfusion in various shock states. Therefore, research was aimed at combining cardiac output measurement with pH measurement to reduce morbidity and mortality. Mythen and Webb performed 2 studies combining noninvasive cardiac output and pH measurement in surgical patients undergoing major surgery (longer than 2 hours and cardiac surgery). A low gastric pH value and normal cardiac output were associated with increased postoperative complications, and using volume expansion to increase the pH value improved the outcome for the patients.

Gastric pH measurement and esophageal Doppler cardiac output were used to direct therapy for patients undergoing major surgery excluding vascular and cardiac surgery. The investigators used more extensive indicators of postoperative dysfunction, using all the body systems, and found that gastrointestinal dysfunction was the most common cause of postoperative morbidity in 320 surgical patients. This, along with another study performed at a similar time, further reinforced the previous findings for improving gastric pH values and cardiac output to reduce postoperative complications.

By using the esophageal Doppler monitor alone, Haxby et al. found that hemodynamic effects were evident in patients requiring general anesthesia for laparoscopic hernia repairs. They studied 10 men, whose average age was 58 years. Along with blood pressure changes (measured by arterial line) and respiratory changes, they observed stroke distance, which is similar to stroke volume, and estimated systemic vascular resistance through the use of the esophageal Doppler. They noted that significant hemodynamic changes occurred after insufflation of the abdomen, but they questioned whether these changes were clinically significant. They further indicated that more invasive hemodynamic monitoring is warranted for patients with higher surgical risks.

Use of the esophageal Doppler monitor in pediatrics

Thus far, little research has been accomplished on the esophageal Doppler monitor in children. However, aims at improving use for this population focus on optimizing pediatric monitoring conditions, with special attention to the least invasive monitor available. For example, pediatric specialists are reluctant to use PACs in children, even when hemodynamic monitoring is warranted. The esophageal Doppler monitor therefore was studied in 11 postcardiac surgery pediatric patients. These patients averaged 39 months of age and had preexisting PACs in place. Simultaneous measurements were obtained, and the authors found that the transesophageal Doppler measurements were reproducible, and the Doppler was easy to use and provided clinically acceptable hemodynamic information.

Comparison of the esophageal Doppler monitor with the PAC for hemodynamic monitoring

Most of the research performed to date on the esophageal Doppler monitor focuses on cardiac output measurement comparisons with the “gold standard” method, thermodilution via the
This Doppler has been studied in a variety of settings, including cardiac surgery, general surgery, and the ICU.

Cardiac surgery poses an area that would benefit from esophageal Doppler monitoring information, since more intensive hemodynamic information is desirable. One area in which the esophageal Doppler monitor has been tested is myocardial revascularization for coronary artery disease. Carrillo and colleagues compared methods of continuous cardiac output monitoring. They found good correlation between the 2 methods after testing in 15 patients undergoing myocardial revascularization. Carrillo et al performed another comparison of PAC and esophageal Doppler cardiac output measurements in the immediate postoperative period following coronary bypass grafts in 30 patients and, again, found excellent correlations \( r = 0.91-0.94 \).

It has long been understood that for the Doppler to provide accurate information, the aortic cross-sectional area needs to be constant during systole. This is true because the stroke distance (measured from the waveform) multiplied by the aortic cross-sectional area provides the estimation of cardiac output. Hence, this monitor theoretically would be useless for estimating hemodynamic values in anyone who had abnormal aortic blood flow, such as patients with aortic stenosis, aortic aneurysms, or abnormal blood pressure. This theory has been tested in such pathological conditions of the aorta, findings conflict. In the 1980s, anesthesiologists compared thermodilution and esophageal Doppler measurements of cardiac output in sheep and concluded that extremes in blood pressure paralleled changes in the aortic cross-sectional area, which resulted in inaccurate cardiac output results. This, however, was not the finding in later work performed during aortic aneurysm repair and aortic valve replacement for stenosis. The findings of Perrino et al also were conflicting; they realized that the esophageal Doppler monitor showed good correlation only before and after aortic cross-clamp, not during.

Although there seem to be contradictory findings about the accuracy of esophageal Doppler cardiac output in aortic pathological conditions, this monitor seems to be quite useful in other situations. Singer and Bennett studied patients undergoing a variety of cardiac surgical procedures or in ICU for a variety of reasons. Patients were divided into 3 groups by condition: (1) increased left ventricular filling, (2) reduced left ventricular filling, and (3) controlled reduced left ventricular filling for left ventricular failure. Cardiac output, pulmonary artery occlusion pressures, corrected flow time, minute distance, and systemic vascular resistance were used to compare the Doppler with the PAC. With the different states of the ventricle, comparable and predictable changes were seen with both devices. Numerous other studies comparing these 2 monitors found similar good correlation with cardiac output in the ICU and during cardiac surgery and liver transplant surgery.

Wong and colleagues compared cardiac output measurements by transit time ultrasound with the esophageal Doppler and the PAC in 7 pigs under general anesthesia. A poor correlation between esophageal Doppler and transit time ultrasound was found, while thermodilution seemed to be more accurate. More specifically, the authors discovered that cardiac output was underestimated during induced changes in preload and contractility and exaggerated in changes in afterload.

**Where does the PAC stand?**

The growing amount of literature in this relatively new field of noninvasive cardiac output monitoring parallels a time when the benefits of the PAC are being questioned. The mortality rates have been evaluated in recent years in patients with myocardial infarction and have been found to be higher when the PAC was used. In addition, as of 1996, a randomized controlled trial has not been performed in the history of this monitor. Therefore, Connors et al studied the association between the use of PAC during the first 24 hours of care in the ICU and subsequent survival, length of stay, intensity, and cost of care (prospective cohort study). A total of 5,735 patients were studied, and they were classified according to disease present by using a propensity score. The investigators concluded that the PAC was associated with increased mortality and use of resources.

It is estimated that 1 million PACs are sold in the United States each year, with costs exceeding $2 billion per year. Presently, its use is limited to extremely ill patients because the risks of its use are so great. Critical conditions that indicate the use of the PAC include myocardial infarction, cardiac tamponade, acute respiratory distress syndrome, and all types of shock. The risks of the PAC include pulmonary artery rupture, pneumothorax during insertion, endocarditis, and ventricular arrhythmias, which can be particularly detrimental to the patient who has just had a myocardial infarction. Other complications of pulmonary artery catheterization are infection,
hematoma, local thrombus, complete heart block, thrombosis, bacteremia, valve damage, pulmonary embolus, and pulmonary infarction.

Because of the complications of the PAC, Dalen and Bone devised some suggestions for the future. One of these suggestions is that the National Heart, Lung, and Blood Institute undertake a multicenter, randomized, controlled trial of the use of pulmonary artery catheterization. Furthermore, they urged ending the use of the PAC in addition to temporarily halting the use of the flow-directed PACs if a randomized controlled trial is not performed.

The safety of the esophageal Doppler monitor in providing hemodynamic data has been studied critically in several areas. Given the PAC’s current status, as evidenced by the aforementioned problems and complications, further validation studies of this technology need to be conducted to ensure availability of an alternative hemodynamic monitor for clinical use. However, the question of the PAC’s future lies in the governmental realm, specifically the US Food and Drug Administration.

Cost and practical issues

The estimated costs of the PAC were stated in the previous section. Deltex Medical, Inc., Irving, Texas, a company that is marketing the esophageal Doppler monitor in the United States, charges $99 for each disposable probe and provides the monitor at no extra charge (M. Ard, Deltex Medical, Inc., verbal personal communication, March 17, 1998). Ard also claims that PACs cost hospitals approximately $120. While this difference is rather small, qualitative costs also need to be considered because the esophageal Doppler requires less time to insert and is less invasive.

The esophageal Doppler monitor would provide a way to observe hemodynamic trends more in depth for patients in whom a PAC is considered too invasive, such as patients undergoing more minor procedures such as orthopedic and laparoscopic procedures. Other patients are those whose diagnoses do not indicate the use of the PAC but who would benefit from more accurate methods for determining fluid repletion needs, as by the esophageal Doppler.

As a noninvasive monitor, the esophageal Doppler is associated with no major complications and few contraindications. For instance, the use of this monitor is not advocated for patients with aortic coarctation or esophageal disorders. Other benefits of the esophageal Doppler monitor that would promote acceptance include its ease of insertion with a steep learning curve. Knowledge of hemodynamic status can be obtained very rapidly after insertion.

It is recommended throughout the literature that the esophageal Doppler monitor should not replace the PAC for advanced hemodynamic monitoring. Rather, it is suggested that the esophageal Doppler be an adjunct to PAC monitoring. Others advise that the esophageal Doppler monitor be used as a stepping stone between basic blood pressure and central venous pressure monitoring, and full invasive monitoring.

Summary

Overall, the esophageal Doppler monitor is a useful method for estimating and trending cardiac output. The values obtained are comparable to those of the PAC and, furthermore, are obtained continuously and noninvasively.

The esophageal Doppler monitor displays other indices of hemodynamic monitoring that aid in fluid management, inotropic therapy, and vasodilator therapy. By merely observing the waveform, these values can be obtained and appropriate interventions can be determined by the practitioner. When the PAC is not deemed necessary, the esophageal Doppler has been shown to be a useful alternative.

More work is vital in this relatively new area of monitoring. Through reviewing the literature available, it is apparent that the future of this monitor in anesthesia is promising. It provides key characteristics that practitioners desire, such as noninvasiveness, safety, and accuracy.

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