Advances in Anesthesia Monitoring

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Technological advances in monitoring for anesthesia continue to provide clinicians with an increasing amount of physiologic information for critical intraoperative decision making. This expanded set of physiologic data not only makes "routine" surgery safer from rare, but potentially fatal, anesthetic or surgical mishaps; it also facilitates surgery on very high risk patients. However, it must be emphasized at the onset that "anesthesia monitoring" is probably more appropriately termed "perioperative" or "critical care" monitoring, since many of these advances are applicable in the critical care units as well.

The ability to monitor *continuously* variables that previously had only been measured *intermittently* (often at very long intervals), including ST-segment analysis, pulse oximetry, capnography, arterial blood gas analysis, etc., should be considered "advances" even if they are not new technologies. All of these may ultimately be of greater value in the critical care unit than in the operating room, where the constant eye of the anesthetist, combined with new specific and shorter-acting anesthetic drugs, have made the actual surgical procedure safer than it has ever been. On the human side, advances in integrated physiologic data displays and our knowledge of human attention and perception facilitate our ability to use more effectively the data we obtain from multiple physiologic monitors. [1] Finally, advances in both automated anesthesia record systems and computerized clinical information management systems capable of extracting data continuously from various monitors, as well as linking directly in real-time to the hospital laboratory and the medical record, will significantly impact on how we deliver healthcare.

However, in this era of sweeping changes in medical economics, with cost containment a major goal of both private and governmental agencies, there are new issues that must be addressed. These include the following: (1) Can practitioners translate an expanded amount of physiologic data into more effective decision making? (2) Can monitoring actually improve patient outcome, specifically morbidity and mortality related to the underlying disease process? (3) In the final analysis, is monitoring "cost-effective"?

Many of the concepts and hypotheses are beyond the scope of this short review. Instead, the focus here is to present to the busy surgeon several recent advances in perioperative monitoring stratified by organ system, all of which have recent or potential clinical application. Given the author's primary practice of adult cardiovascular anesthesia, a somewhat greater emphasis is given to cardiac monitoring.

CARDIAC MONITORING
ELECTROCARDIOGRAPHIC TECHNIQUES

Since perioperative myocardial infarction is perhaps the most feared "non-surgical" complication and one that has resulted in triaging the greatest number of adult surgical candidates away from surgery, much emphasis has been placed on monitoring for myocardial ischemia. Advances on a number of fronts, particularly in better preoperative evaluation and therapy, as well as more sophisticated monitoring, have resulted in a striking decrease in the incidence and morbidity/mortality related to perioperative MI over the past decade.

Although most cardiologists would ascribe these improved statistics to advances in preoperative modalities such as dipyridamole-thallium imaging, there is evidence suggesting that a further reduction in morbidity may still be possible using more effective electrocardiographic ST-segment monitoring. Studies have shown that ST-segment depression during preoperative Holter monitoring may be as predictive as dipyridamole-thallium imaging for risk stratification. [2] For patients already operated on, repetitive episodes of intra- and postoperative ST-segment depression usually precede a myocardial infarction. [3] The vast majority of these episodes occurs in the absence of chest pain (so-called "silent myocardial ischemia"). Although no study as of yet has conclusively shown that aggressive recognition of these episodes results in improved outcome, such a hypothesis is not unreasonable and is being pursued by several research groups.

The technology to detect and quantify these episodes of asymptomatic ST-segment changes is now widely available. [4] Nearly all clinicians have been exposed to computerized electrocardiography, since nearly all 12 lead ECG machines in use in industrialized countries now utilize computerized diagnosis and digital storage of data. In addition, treadmill exercise systems and continuous Holter recording systems also utilize digital processing.

Since the introduction of computerized ST-segment analysis software into operating-room and intensive-care unit bedside hemodynamic monitors a decade ago, nearly all manufacturers have followed suit. This technology still has problems related to (1) a lack of standardization for accuracy and performance among manufacturers and regulatory agencies, (2) occasional errors that may result from a lack of such standards, (3) limitations in the ability to store all data necessary for visual confirmation of trend-line changes, and (4) problems related to alarms based on ST-segment changes. Nevertheless, by far the greatest limitation is on the human side. [5] Although anesthesiologists have placed significant emphasis on proper use of this technology in the operating room, it has not been widely accepted in the critical care units or on the surgical wards. Until such time that clinicians and nurses are willing to put the extra effort required into using it properly, it is unlikely that its potential benefits will be recognized.

ECHOCARDIOGRAPHIC TECHNIQUES

In the late 1970s the first echocardiographic transducers were mounted onto gastroscopes allowing the advent of transesophageal echocardiography. Although initial interest in its use by cardiologists was based primarily on its ability to visualize atrial and valvular structures missed on transthoracic echocardiography, it was quickly appreciated that it had significant potential for real-time monitoring of cardiac function during operative procedures, since the transducer would not usually interfere with the surgical procedure.

Visualization of regional wall motion abnormalities–changes caused by myocardial ischemia considered to be more sensitive than electrocardiographic changes–may assist in recognizing and treating patients at risk for perioperative myocardial infarction. [6] It has also been shown that major changes in wall motion can be easily recognized by anesthesiologists with minimal formal training in echocardiography. Based on practice surveys and attendance at academic meetings, a rapidly growing number of cardiovascular anesthesiologists have incorporated this monitoring into their clinical practice. Although wall motion

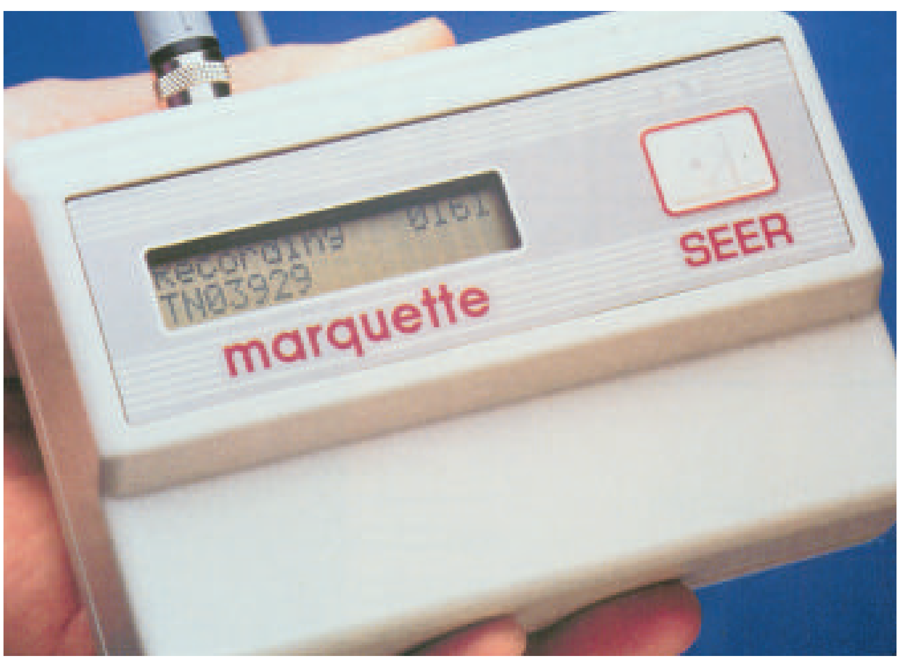

Figure 1. New digital technology allows sophisticated real-time ECG data analysis to be incorporated into portable Holter monitors. These devices have significant potential to be used for detecting postoperative episodes of silent myocardial ischemia which identify patients at highest risk for myocardial infarction.

Figure 2. With the growing use of intraoperative two-dimensional and Doppler transesophageal echocardiography, anesthesiologists can obtain valuable information about myocardial ischemia and infarction, valvular function, volume status, contractility, and even cardiac output.

abnormalities are usually a manifestation of acute myocardial ischemia, some controversy exists regarding their specificity (particularly with major changes in afterload and contractility). It is also important to distinguish them properly from chronic changes due to previous myocardial infarction. The phenomenon of "myocardial stunning," in which an acute protracted reduction in wall motion may occur despite restoration of normal coronary blood flow (a relatively common occurrence following removal of the aortic crossclamp during myocardial revascularization), further complicates interpretation. However, new methods including "color encoding" wall motion, as well as the use of "tracer agents" capable of delineating changes in myocardial blood flow ("perfusion echocardiography"), continue to advance the state of the art. [7]

In addition, transesophageal echo allows recognition of changes in intravascular volume, cardiac output and contractility, and valvular function. Advances in signal processing allow automated real-time detection of the boundary between the endocardium and the ventricular cavity blood pool (so-called "acoustic quantification"). [8] This interesting approach has been shown to have potential application for on-line assessment of ventricular function and intravascular volume. When coupled with pressure monitoring, it may allow real-time assessment of load-independent measures of contractility. Measurement of cardiac output with TEE is also possible with a high degree of accuracy. [9] However, this requires advanced training, is not always technically possible, and takes significantly longer than the thermodilution method.

More recently, TEE has been shown to have value in detecting severe atheromatous disease in the ascending aorta, a finding correlated with increased risk of stroke during cardiac surgery from embolization during placement of the aortic crossclamp or cannula. Although acoustic shadowing from the trachea and bronchi limit imaging of the proximal portion of the ascending aorta, an area better inspected by the surgeon with an "epiaortic" probe, TEE still can be of value in recognizing high-risk patients needing closer examination.

Although refinement in each of these uses will require more time to make them highly accurate and easily quantified by all anesthesiologists, major advances in transducer technology and the introduction of digital echo machines should ensure greater clinical application of this technology in the coming decade. However, the considerable expense of this technology and the advanced training required to utilize it properly are major issues that need to be addressed. The recent formation of a joint task force by the American Society of Anesthesiologists and the Society of Cardiovascular Anesthesiologists to develop practice parameters for perioperative transesophageal echocardiography performed by anesthesiologists is a valuable first step in this direction.

MONITORING CARDIAC OUTPUT AND OXYGEN DELIVERY

Of all of the cardiac measurements made clinically, most would agree that cardiac output is probably most important. An adequate cardiac output in the absence of signs of tissue acidosis is usually considered to be an adequate endpoint of therapy (in the absence of focal

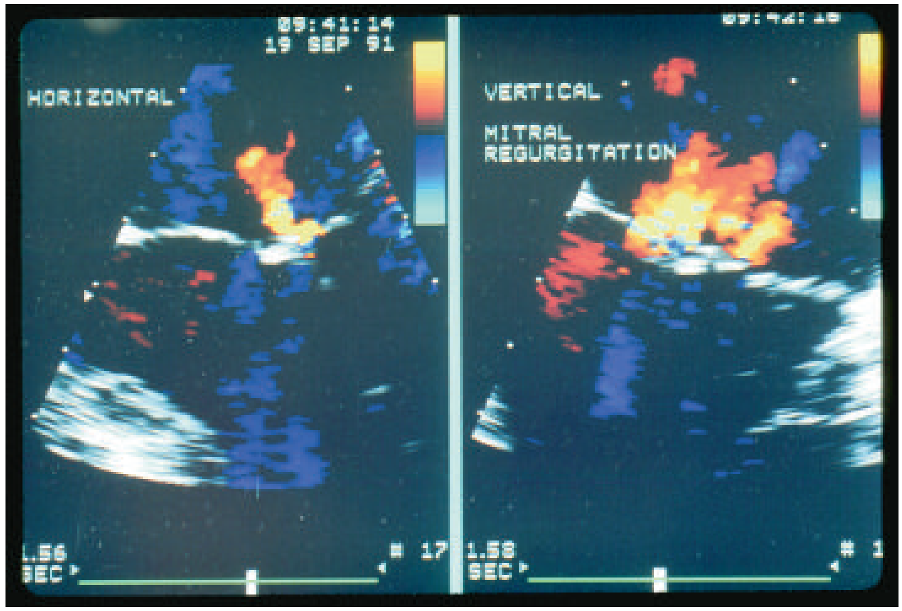

Figure 3. Biplane TEE probes in which two transducers are arranged orthogonally allow more precise visualization of anatomic abnormalities in two planes as illustrated by the mitral regurgitation detected by color flow Doppler imaging.

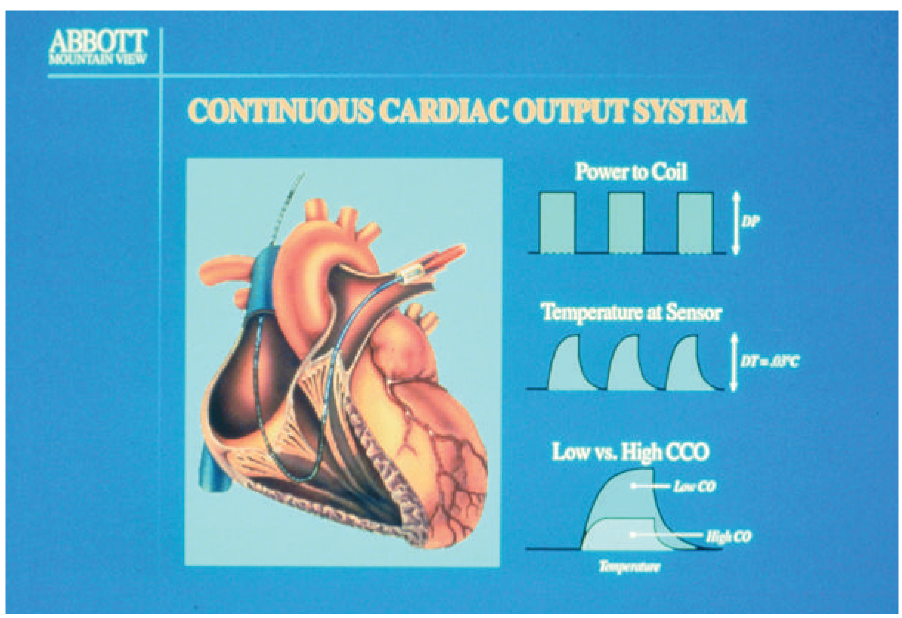

Figure 4. "Pulsed" thermodilution technology allows continuous cardiac output determination via a thermal filament on the PA catheter that is intermittently heated, causing a distal change in temperature at the thermistor. This technology will most likely see widespread use in critical care units. (Reprinted with permission, Abbott Laboratories, Mountain View, Calif.)

ischemic disease in the heart or central nervous system). Although nearly all cardiac output measurements are made using thermodilution methodology via a pulmonary artery catheter, this technique involves the hazards of catheterization and is limited by intermittent measurements.

The quest for an accurate, noninvasive method for measuring cardiac output has been frustrating. Using continuous Doppler technology, probes inserted into the esophagus and even on the end of an endotracheal tube have been investigated as a means to interrogate the ascending or descending aorta.[10] However, this technology has not been widely accepted due to problems with variable size and cross-sectional area of the region of the aorta being assessed and by problems with movement of the probe. In addition, these methods are of limited value in the critical care units in awake patients. Although noninvasive bioimpedence methodology is accurate in healthy subjects, it is severely limited in critically ill, nonstable patients.

Despite its invasivity, the pulmonary artery catheter is widely used perioperatively, and new methodology for continuous cardiac output determination makes its increased use likely. This technology (termed "pulsed thermodilution") uses a sensitive thermal filament to provide intermittent periods of heat which are detected along the distal portion of the catheter. Sophisticated stochastic signal processing generates a thermodilution washout curve which provides an average cardiac output measurement over a several minute period, updated every 30 seconds. This system also has the advantage of not requiring any exogenous injectate. Initial clinical studies are very favorable.[11] However, this system requires a stable thermal environment and thus is of very limited value in the intraoperative period, particularly during cardiac surgery. Although earlier versions of this methodology capable of measurement of right ventricular ejection fraction have been available for over five years, this technology has not seen widespread clinical use.

The use of fiber-optic technology for continuous measurement of mixed venous oxygen saturation allows measurement of multiple aspects of tissue oxygen balance. The value of this technique is that it reflects dynamic changes in cardiac output, hemoglobin concentration, arterial oxygen saturation, and total body metabolic rate. However, its major limitation is that it fails as a single monitor to specify which of these variables has changed. It has been suggested that its best use is to provide a "continuous early warning system" that one or more of these have changed. It can be of particular value in weaning difficult patients from mechanical ventilation. Its cost-effectiveness has been challenged in several studies, although this remains controversial.[12,13] With the introduction of pulsed thermodilution, it is likely that it will assume less importance, although at least the manufacturer will provide it along with pulsed thermodilution for no additional cost.

RESPIRATORY MONITORING

Monitoring of oxygenation and ventilation are of particular interest to anesthesiologists. Continuous pulse oximetry, which monitors peripheral oxygen saturation (SpO_2), which is an indirect but nonetheless valuable measure of arterial oxygen saturation (S_aO_2), has been the single greatest factor responsible for a major reduction in malpractice premiums for anesthesiologists.[14] When properly used along with continuous measurement of exhaled

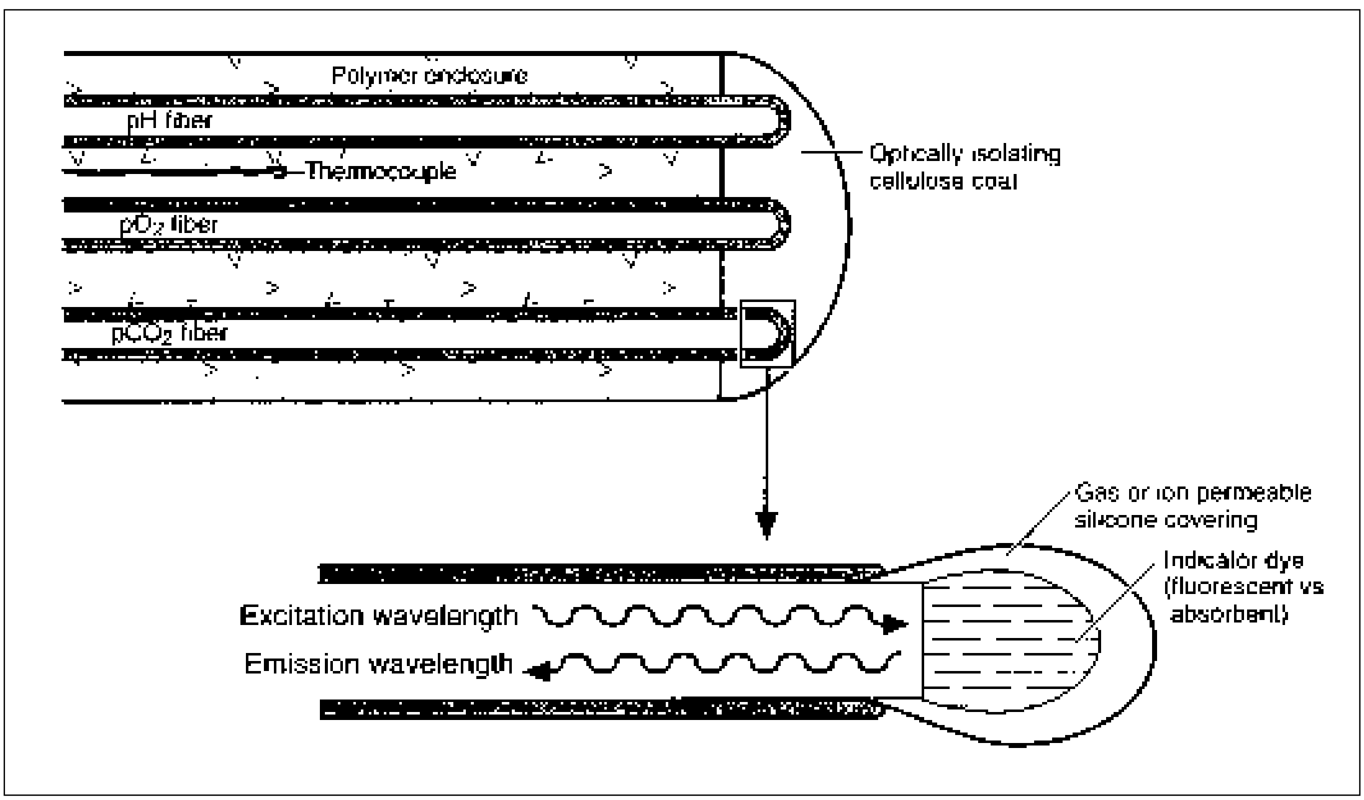

Figure 5. Flourescent "Optode" technology allows continuous measurement of arterial blood gas parameters. However, clinical implementation of this technology has been limited due to technical problems related to intravascular placement of these sensors. (Reprinted with permission from Wahr JA, Tremper KK. Continuous Intravascular Blood Gas Monitoring. J Cardiothorac Vascular Anesthesia 1994;8:342-353.)

carbon dioxide concentration, it virtually assures the anesthesiologist of proper placement of the endotracheal tube in the trachea, eliminating the catastrophic unrecognized esophageal intubation responsible for multimillion dollar malpractice settlements.

Advances in pulse oximetry continue to be made, although the technology still suffers from problems related to its inability to read accurately saturation with decreased peripheral tissue perfusion.[15] This is a major problem since reductions in body and skin temperature, along with sympathetically mediated peripheral vasoconstriction, are so common in the perioperative period. The problem is amplified in the critical care units where, in the authors experience, many experienced nurses report erroneously low data based on a failure to appreciate that the digital value of SpO_2 is only as good as the quality of the tracing it is derived from.

In this regard, the introduction of technology capable of continuous arterial blood gas analysis allowing measurement of pH, oxygen, and carbon dioxide tension has significant potential.[16] This unique technology is based on fluorescent "optode" technology which consists of an optical fiber with a fluorescent dye at the end. Light of known intensity is pulsed to the dye. Changes in the fluorescence of this dye in relation to the known excitation source, are linearly related to pH and carbon dioxide (augmented) or oxygen (diminished). Although this technology is commonly used on cardiopulmonary bypass machines, its application to optodes positioned in an indwelling radial artery catheter has been slower and more problematic related to changes in the position of the catheter in relation to the bloodstream. However, modification of this approach, in which the sensor is positioned outside the body and blood is intermittently aspirated into a rapid-response sensing chamber, is more likely to be useful.

MONITORING THE NERVOUS SYSTEM

Of all the organ systems, changes in nervous system function are most closely linked to the actual "depth of anesthesia." However, with rare exceptions, clinical monitoring is limited to qualitative assessment of loss of consciousness (e.g., loss of eyelid reflex). Some of the reasons for this include an incomplete knowledge of neurophysiology, and the complexities of action of a variety of different anesthetic drugs. Additional training is required to interpret several different modalities properly, based on the fact that the operating theater is an electrically hostile environment to the low-voltage potentials of the electroencephalogram (EEG) and to other electrical potentials that can be monitored. Although it is unlikely that neurologic monitoring will be used routinely on healthy patients in the near future, advances continue to be made that may significantly improve outcomes in high-risk patients undergoing major surgery, particularly intracranial, carotid, spinal, and open heart surgery.

The EEG has been used intraoperatively in a small number of centers for many years. Since it is one the most commonly used diagnostic tools for detecting cerebral pathology, there is much literature on its uses and limitations. Its major limitation remains the simple fact that each electrode interrogates only a very limited volume of cerebral mass, thus the need for an array of electrodes which greatly limits its clinical use.[17] However, there has been great progress in signal acquisition and analysis methods that allow display of the "compressed spectral array" in which simple patterns of "mountains and valleys" can quickly show significant changes in cerebral functioning that are easily recognized with minimal training. Despite commercial marketing of several devices (using a limited electrode array) with this type of display, clinical use remains very limited.

The newest developments in this area include transcranial Doppler, jugular venous bulb oxygen saturation, and cerebral oximetry. The first consists of a head strap containing a Doppler velocity transducer which is positioned over the temporal portion of the middle cerebral artery. This technique allows sensitive detection of emboli during cardiac surgery which have been associated with a decline in postoperative cognitive function.[18] However, this method is unable to differentiate between air and particulate emboli; the correlation of emboli with cognitive functioning is not well "calibrated." Monitoring of jugular venous bulb oxygen saturation may be a more valuable clinical tool for cardiac surgery when using a standard fiber-optic mixed venous oxygen saturation catheter, advanced retrograde in the internal jugular vein, despite its invasivity.[19] Major reductions in saturation have been shown to occur during rewarming on bypass which have also been associated with impaired cognitive function. It is possible that this device may guide rewarming which is often done rapidly and may be particularly dangerous in patients with cerebrovascular disease. The newest technology involves the use of near-field optical spectroscopy to measure noninvasively regional cerebral oxygen saturation.[20] This measurement consists primarily of venous saturation, but continuing work in this area may allow measurement of oxyhemoglobin, cytochrome a,a3 redox status, and even cerebral blood volume.

CONCLUSIONS

Advances in monitoring continue to provide exciting new physiologic information for anesthesiologists and surgeons caring for perioperative patients. Advances in computer technology have generally allowed these devices to become easier to use, smaller in size, more stable, and more noninvasive, characteristics particularly important in the busy perioperative environment. Obviously, an acceptable cost-benefit ratio is critical for routine acceptance of any new technology. The future promises to bring many changes that can only help to improve patient outcome. STI

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