

CLINICAL CONCEPTS AND COMMENTARY

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Real-time Intraoperative Monitoring of Myocardial Ischemia in Noncardiac Surgery

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FOR the past 15 yr, there has been intense interest in the anesthesia community in the detection of intra- and postoperative myocardial ischemia as a means of optimizing patient care because of the accumulated evidence suggesting a strong association with perioperative cardiac morbidity and long-term outcome.^{1,2} It is important to understand the limitations of the methods of detecting myocardial ischemia. This review will focus on understanding the current state of real-time intraoperative ischemia monitoring, while the reader is referred to other articles that highlight the importance of emergence and postoperative myocardial ischemia.^{3,4} Although this review focuses on noncardiac surgery, many of the data were obtained from the cardiac surgical patient because of the lack of studies in the noncardiac surgical population. It is thought that data from patients undergoing cardiac surgery may be applied to those undergoing other surgical procedures.

Electrocardiography

The simplest and most cost-effective method of detecting myocardial ischemia is electrocardiography. It is hard

to imagine that electrocardiography was not available as a portable monitor as recently as 1950 because of limitations in the technology. The diagnosis of myocardial ischemia by electrocardiogram changes focuses predominantly on the ST segment. The importance of the development of ST-segment changes on exercise treadmill testing and long-term survival has been shown in multiple studies.⁵ Ventricular ectopy, particularly ventricular tachycardia, may also be related to myocardial ischemia, and this diagnosis should be considered in patients at risk for significant coronary artery disease (CAD).

The relation between ST-segment changes and perioperative myocardial infarction was initially established by a series of articles beginning in 1985.⁶ At that time, intraoperative computerized analysis of the electrocardiogram was used only for research purposes. However, several studies have shown that visual detection of significant ST-segment changes (particularly those of short duration) is extremely poor, ranging from 0 to 46% of episodes detected by visual inspection.^{3,4} With the advent of the newer computerized systems, the ability to accurately and continuously monitor the electrocardiogram for changes indicative of myocardial ischemia has become routine.

Changes indicative of myocardial ischemia are horizontal or downsloping ST-segment depression or ST segment elevation of at least 1 mm (0.1 mV). T-wave inversions and R-wave changes are also associated with myocardial ischemia, although numerous factors (particularly electrolyte changes) can lead to these findings. The depth of ST-segment depression has been used as a measure of the severity of myocardial ischemia. There are baseline abnormalities that make interpretation of the ST segment difficult or impossible; for example, both left bundle branch block and Wolff-Parkinson-White syndrome alter repolarization, which can lead to nonischemic ST-segment changes. Definitions of a significant

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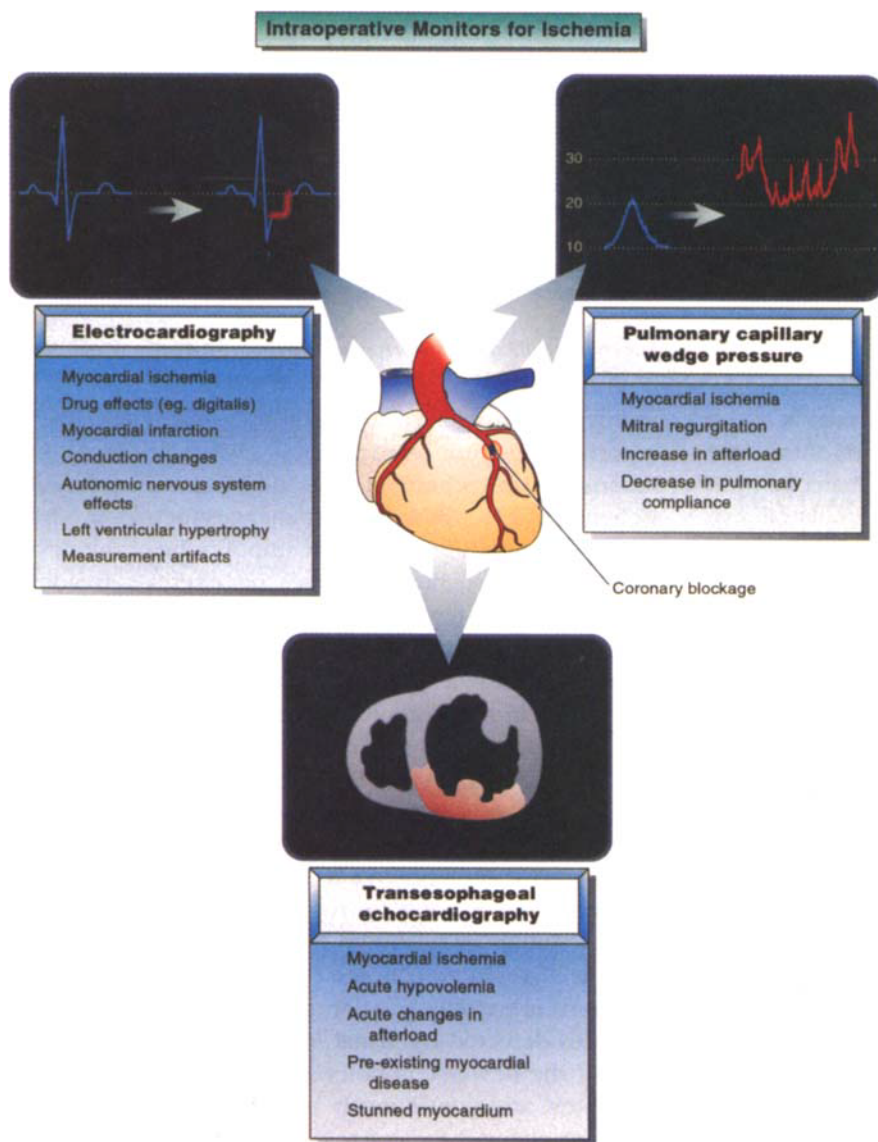


Fig. 1. Cause of "ischemic" changes on intraoperative monitors.

ST-segment shift are also difficult when there is baseline ST-segment depression or left ventricular hypertrophy with strain. In patients with baseline abnormalities, one approach is to consider a 1-mm change from baseline as significant. To increase the specificity of ST-segment changes for myocardial ischemia in patients with left ventricular hypertrophy, a larger change from baseline may be necessary (e.g., 1.5 mm), whereas adjustment for the R-wave amplitude has been advocated in the stress test literature.⁷ However, this approach reduces the sensitivity of electrocardiography to detect myocardial ischemia, and most clinicians will begin treatment when the

ST-segment change reaches 1 mm in patients at high risk for development of myocardial ischemia.

Because detection of ST-segment changes of the electrocardiogram by visual inspection is poor, computerized analysis has become standard in modern monitors. The monitor calculates the difference in millivolts or millimeters between the isoelectric and J point plus 60 or 80 ms. Several issues are related to the accuracy of the reproduction of the electrocardiogram and the algorithms used to measure the ST-segment shift in real time (fig. 1). The isoelectric and J points frequently are set by default by the computer algorithm. If the set points are

incorrect, the extent of ST-segment changes calculated by the monitor may be inaccurate. Before beginning the surgical procedure, the accuracy of the electrocardiographic set points should be determined for the individual patient. This can be accomplished by review of the template selected by the monitor. Thereafter, if the computer algorithm reports significant changes, electrocardiographic strips should be printed to ensure accuracy is maintained because the QRS complex may have changed and produced further inaccuracies.

The accuracy of the ST-segment trend also depends on the algorithms developed by each of the monitoring manufacturers to measure the ST-segment depression or elevation from baseline. These algorithms are proprietary, and the accuracy of the algorithm is not a requirement for its approved sale as part of the monitoring device. In fact, the variability in these algorithms has led the American Heart Association to call for standards.

The variability in accuracy between the different monitors has been evaluated in several studies compared with off-line analysis of standard Holter recordings.⁸⁻¹⁰ ST-trending monitors were found to have an average sensitivity and specificity of 74% (range, 60-78%) and 73% (range, 69-89%), respectively.⁸ Several factors have been identified that decreased the accuracy of the monitors, many of which are highlighted herein. One of the strongest factors for inaccurate ST trends was the presence of a small R-wave amplitude.

Another issue is the filter system used. The traditional American Heart Association recommendations for monitoring the electrocardiogram include a bandwidth of 0.05-100 Hz. To minimize the baseline drift caused by mechanical ventilation and poor electrode contact, a more narrow bandwidth may be used; *i.e.*, the lower cut-off is set at 0.5 Hz in the monitoring mode of standard systems. The ST segment may appear to have more of a square wave or a horizontal-appearing depression than would be observed using the full bandwidth. The influence of these filters can lead to different incidences of significant ST-segment changes, as shown in a study by Slogoff and Keats.⁹ The shape of the ST-segment change can also influence the accuracy of the computerized analysis. Increases of heart rate can lead to depression at the J point (>1 mm) and an upsloping ST segment, which the computerized analysis may report as significant depression. Such changes are not indicative of CAD or myocardial ischemia, but are a function of repolarization changes at increased heart rates.

The choice and configuration of the leads used for monitoring may influence the ability to detect significant

ST-segment changes. Artifacts can be generated by poor lead contact related to a lack of preparation of the skin. Literature from exercise stress test suggested that leads II and V₅ detect 96% of all significant ST-segment changes observed with 12-lead electrocardiography. Much of the research regarding perioperative ischemia has used Holter recorders. Holter recorders use bipolar lead systems, usually with one lead placed at a point at the top of the sternum and the other at the V₃ or V₅ chest position. The bipolar vector is different from the unipolar vector of 12-lead electrocardiography (in which chest leads use a point in the center of the chest for the origin of the electrocardiographic vector), which can again change the degree of ST-segment shift. London *et al.*¹¹ studied the ability of different lead systems to detect intraoperative ST-segment changes and found that combining leads II and V₅ only detected 80% of all significant ST-segment changes. The addition of a third lead, V₄, was necessary to increase the sensitivity to 96%. Because current monitors do not allow the user to select two chest leads, the greater degree of sensitivity afforded by the use of a V₄ lead is not available routinely intraoperatively.

Assuming that the ST-segment trend monitor has accurately identified a significant ST-segment change, what is the relation between these ST changes and actual myocardial ischemia? As with any diagnostic test, as stated in Bayes theorem, the post-test probability of disease is a function of the pretest probability. In simple terms, significant ST-segment changes represent ischemia in a population with a high prevalence of CAD. Similar changes in younger individuals or those with a low probability of disease may not represent myocardial ischemia. In the perioperative period, the importance of the prior probability has been shown by the high incidence of significant ST-segment changes in pregnant women undergoing elective cesarean section and adults older than 40 years with only one risk factor for coronary disease but no atherosclerotic process.^{12,13} Neither group showed the presence of CAD by either intraoperative echocardiography or exercise stress test after surgery, respectively. In contrast, the clinician should assume that all ST-segment changes in vascular or cardiac surgical patients are a type of myocardial ischemia until proven otherwise. In a series of studies during the past decade, the presence of these changes in high-risk cohorts has been linked to a higher incidence of perioperative myocardial infarction and cardiac events. In addition, the duration of ST-segment changes correlates positively with the incidence of perioperative myocar-

dial infarction.¹⁴ Therefore, when ST-segment changes occur, the clinician should assume that myocardial ischemia is present if the patient has a history of preexisting cardiac disease or is undergoing surgery for which patients generally are at high risk for CAD.

Pulmonary Artery Catheter

The pulmonary artery catheter has been advocated as a means of detecting myocardial ischemia. The development of myocardial ischemia can lead to acute increases in the pulmonary capillary wedge pressure (PCWP) from changes in systolic performance and ventricular compliance. If myocardial ischemia either is global or involves the papillary muscle, V waves indicative of papillary muscle dysfunction and mitral regurgitation may develop. The sensitivity and specificity of an increase in the PCWP for myocardial ischemia depends on the specific criteria used, with a greater increase showing improved specificity but lower sensitivity.

Increases in PCWP may be of ischemic and nonischemic cause. For example, acute increases in afterload, decreases in pulmonary venous compliance, and mitral regurgitation of nonischemic origin can all lead to the changes described previously. PCWP may not increase in relation to ischemia because significant changes in ventricular compliance must occur first. If only small regions of myocardium become ischemic, overall ventricular compliance may be unchanged. Finally, the PCWP is not continuously monitored intraoperatively because of potential complications, and the pulmonary artery diastolic pressure is even less sensitive in detecting a change in ventricular compliance than is PCWP.

In one of the only systematic studies of PCWP monitoring for myocardial ischemia in noncardiac surgery, Haggmark *et al.*¹⁵ measured changes in PCWP in 53 vascular surgery patients with CAD and compared it with indices of myocardial ischemia, as determined by the electrocardiography, cardiokymography, or myocardial lactate production. An increase in PCWP or the presence of A-C or V waves greater than 5 mmHg above the mean did not reflect ischemia reliably. The American Society of Anesthesiologists practice guidelines for the pulmonary artery catheter does not specifically address the value of the pulmonary artery catheter for ischemia monitoring. There are no randomized trials in selected patients undergoing noncardiac surgery in which the use of a pulmonary artery catheter is associated with improved outcome.¹⁶ However, information from the pul-

monary artery catheter can be used to guide treatment in the patient with myocardial ischemia. Specifically, the PCWP can be used to direct fluid and vasopressor and vasodilator therapy.

Transesophageal Echocardiography

The development of new regional wall motion abnormalities as detected by transesophageal echocardiography (TEE) has become a *de facto* standard for the intraoperative diagnosis of myocardial ischemia. The *Practice Guidelines for Perioperative Transesophageal Echocardiography* from the American Society of Anesthesiologists and the Society of Cardiovascular Anesthesiologists has recently evaluated the existing research regarding the use of TEE to measure ischemia. The panel concluded that TEE can detect regional ventricular dysfunction, but there is little evidence of its accuracy or evidence that wall motion abnormalities reflect true myocardial ischemia.¹⁷ It is argued that the high incidence of intraoperative ventricular dysfunction on TEE raises important questions regarding the false-positive rate of the technology. However, in patients in whom myocardial ischemia develops, the experts suggest that wall motion abnormalities occur before electrocardiographic changes.

Several hemodynamic abnormalities can lead to new segmental wall motion abnormalities in the absence of myocardial ischemia. Acute hypovolemia (reduction in cardiac filling) has been shown to lead to new systolic wall motion abnormalities in patients with preexisting abnormalities of left ventricular contraction.¹⁸ Acute changes in afterload also may lead to segmental wall motion abnormalities. The effect of afterload can be seen in a study of patients undergoing aortic aneurysm surgery, in which the incidence of segmental wall motion abnormalities increases with a more proximal level of aortic clamping. In that study, abnormalities developed in virtually all patients because of placement of a supraceliac aortic clamp.¹⁹

There are several limitations regarding the use of TEE for intraoperative ischemia detection. Currently, the equipment is expensive and necessitates a great deal of maintenance. It necessitates extensive training to ensure accurate interpretation, which led to the development of a certification examination administered by the National Board of Echocardiography. Importantly, TEE can only be used during general anesthesia; however, many high-risk noncardiac surgical patients have regional anesthe-

sia. Because the probe is inserted after induction of general anesthesia, a period during which ischemia may develop, the TEE is not available during a critical period. Finally, the development of myocardial ischemia can result in myocardial "stunning," whereby the myocardium continues to exhibit diminished contractile function despite the resolution of ischemia. Therefore, the TEE may help to detect ischemia but may continue to exhibit persistent wall motion abnormalities even after the ischemia resolved.

One method proposed to improve the real-time identification of regional wall motion abnormalities has been the development of real-time edge-detection algorithms. Only quantitative wall motion assessment is available in real time, which may be less accurate than off-line assessment. Importantly, only one plane can be assessed and, therefore, ischemia that occurs in the nonvisualized myocardium may go undetected. Despite these attempts, there are no commercially available systems for real-time ischemia detection in widespread use.

For noncardiac surgery, a technology evaluation of TEE, two-lead electrocardiography, and 12-lead electrocardiography showed a minimal additive value of TEE over two-lead electrocardiography.²⁰ A total of 10 cardiac events occurred in a total population of 285 high-risk patients. In a retrospective analysis of the data, only one additional cardiac event would have been detected by TEE compared with the electrocardiographic methods, although a higher percentage of patients with myocardial ischemia was observed. Although TEE for routine monitoring of intraoperative ischemia in noncardiac surgery may have a minimal additive value over analysis of ST-segment trends for predicting patients who will sustain perioperative morbidity, TEE monitoring may be extremely valuable to direct treatment-diagnostic dilemmas.

In summary, electrocardiography, pulmonary capillary wedge pressure monitoring, and TEE are viable methods of detecting intraoperative myocardial ischemia in real time, but the sensitivity and specificity varies greatly. Analysis of ST-segment trends offers a simple and noninvasive method of detecting myocardial ischemia and should be evaluated routinely in all high-risk patients. The interpretation of ST-segment changes for detection of myocardial ischemia depends on monitoring factors and the population studied. The sensitivity of PCWP changes for detecting myocardial ischemia is poor, but the information provided by the monitor may help to guide fluid and vasopressor management. New regional wall motion abnormalities associated with myocardial ischemia occur before electrocardiographic changes,

but the expertise necessary for interpretation of TEE imaging to detect wall motion abnormalities, the costs of the technology, and its predominant use in intubated patients limit the widespread adoption of TEE for noncardiac surgery. However, if a difficult diagnostic dilemma develops intraoperatively, insertion of a TEE can quickly provide information to guide treatment.

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