Review Article

Intraoperative automated ST segment analysis: a reliable 'Black Box'?

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Purpose: To review the application of intraoperative computerized ST analysis and its potential impact on postoperative outcomes.

Source: Existing anaesthesia and cardiology literature.

Principal findings: Computerized ST analysis was introduced into the operating room using exercise electrocardiographic (ECG) systems. In spite of sophisticated algorithms, errors do occur. Downsloping or horizontal ST depression are the classical criteria for ischaemia. Although algorithms have been developed and evaluated in exercise stress testing, only limited evaluation has been carried out in the operating room. This may be a concern since circumstances in the operating room may frequently lead to false positives. Similarly, studies suggest that all myocardial ischaemia may not exhibit ST changes. The diagnostic accuracy of ST depression in exercise stress testing also cannot be assumed in the operating room. Finally, if ST analysis is applied widely, without considering the population or disease prevalence, misdiagnosis may occur.

Conclusion: Given the number of anaesthetic tasks at-hand, on-line computerized ST analysis in the operating room can be a useful asset. The technology has its problems and should be

applied with an understanding of its limitations and potential for errors. It should be applied in the operating room within the context of the population and disease prevalence.

Objectif: Revoir l'utilisation peropératoire de l'analyse du segment ST informatisée et son impact potentiel sur le pronostic postopératoire.

Source: La littérature anesthésique et cardiologique actuelle.

Données principales: L'analyse informatisée du segment ST a fait son apparition en salle d'opération après les épreuves électrocardiographiques d'effort. Malgré la perfectionnement des algorithmes, des erreurs surviennent. Les sous-décalages en pente descendante et horizontaux représentent les critères classiques de l'ischémie. Bien que des algorithmes aient été développés et évalués en ce qui concerne l'épreuve d'effort, l'évaluation demeure incomplète pour la salle d'opération. Dans certaines conditions propres à la salle d'opération, l'incidence des faux positifs est alarmante. Des études suggèrent en outre que l'ischémie myocardique peut exister sans que des changements se manifestent au niveau du segment ST. Contrairement à l'épreuve d'effort, on ne peut présumer de la précision de la dépression du segment ST en salle d'opération. Finalement, des erreurs de diagnostic peuvent survenir si l'analyse du segment ST est généralisée sans qu'on tienne compte du type de population et de la nature de la maladie.

Conclusion: En anesthésie, considérant le nombre de tâches à accomplir, l'analyse du segment ST informatisée et « en ligne » en salle d'opération peut être utilisée avec avantage. Cette technologie pose des problèmes et doit être pratiquée en respectant ses limites et de son potentiel d'erreurs. Son utilisation en salle d'opération doit tenir compte du type de population et de la nature de la maladie.

Key words

MONITORING: electrocardiography;

HEART: ischaemia;

COMPLICATIONS: myocardial ischaemia;

ANAESTHESIA: cardiac;

ANAESTHESIA: general.

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Summary

Electrocardiographic (ECG) ST segments have long been advocated as a means of detecting intraoperative myocardial ischaemia. With the advent of computer technology, ST segment analysis has become an automated process and can be monitored in real-time. Due to the ease of application, its use in the operating room has become widespread. This article will review the principles behind ST segment analysis as well as the history of its development. The usefulness of ST segments in predicting and altering the incidence of perioperative outcomes will also be reviewed. The initial literature search was confined to the anaesthesia and cardiology literature from 1965 to 1995. A subsequent search for supporting and historical documentation included earlier publications dating back to 1895.

Pathophysiology

The basis of ST segment analysis is the measurement of ST segment drift against a baseline defined by the PR or TQ segment (Figure 1). In the presence of myocardial ischaemia, ST segments may become depressed. There are two possible mechanisms for ST depression. During the action potential cycle of a cardiac myocyte, ST segment depression occurs during phase-two depolarization. The "systolic current" theory proposes that myocardial ischaemia leads to a decrease in intracellular potassium concentration and, hence, a decrease in phase-two depolarization. The decrease in action potential or voltage is manifested as ST depression. Alternatively, the "diastolic current" theory proposes that elevation of the baseline produces an effect similar to ST depression. This may result when the resting membrane potential in a localized area is decreased, as may be seen during ischaemia. Depression of the ST segment or elevation of the baseline may be distinguishable in direct current recordings. In alternating current

FIGURE 1 In ST segment analysis, the PR or TQ segments are used as the baseline. ST depression can be the result of ST segment depression or of baseline elevation. In computerized analysis, ST depression is usually measured 60 msec from the J point and compared against a point on the PR segment.

recordings, which is the modality most commonly used in clinical settings, the PR/TQ segment is normalized electrically and the two types of change become indistinguishable. Diastolic current is believed to be the more likely mechanism and systolic current is thought to be less specific for myocardial ischaemia.¹

Historical perspectives

Much of the work on ST analysis originates in exercise stress testing. The first documentation of ECG changes associated with angina pectoris was published in 1918.² The patient had been previously diagnosed with aortic insufficiency as well as angina, which he experienced during a recording of his ECG, showing transient right bundle branch block. In 1928, ST depression and T wave inversion, considered now to be the typical changes with myocardial ischaemia, were reported during anginal episodes.³ In 1931, a report on ECG changes during exercise appeared.⁴ In this description of what was essentially the first exercise stress test, the following concluding comments were made:

"The use of our electrocardiographic procedure to diagnose angina pectoris is not recommended... Moreover, 50 per cent of cases give no diagnostic electrocardiographic phenomena, and the significance of changes that may appear in the ventricular complex is still open to question..."⁴

Only leads I, II, and III were used and the poor diagnostic value was attributed partly to the number of leads used. In a subsequent study, the addition of a fourth chest lead was deemed invaluable.⁵ The introduction of an exercise protocol increased the test's accuracy and helped to secure exercise stress testing as a diagnostic tool in coronary artery disease.⁶

In 1964, twelve-lead ECGs were recorded sequentially and immediately after exercise.⁷ Of the ischaemic

episodes seen on ECG, the precordial leads were the most sensitive: 89% of the ST depression was seen in V_5 although multiple leads provided further increases in sensitivity. This was confirmed by other studies, often with a slight decrease in specificity.⁸ In the early days of stress testing, ECGs were not recorded during exercise due to motion artifacts. Subsequent studies seemed to show little compromise of reliability when limb leads were placed on the torso.⁹ Twelve-lead ECGs were then recorded both during as well as after exercise. The additional ECG tracings during exercise provided a further diagnostic yield in 9% of the patients.¹⁰

Computerized ECG acquisition and processing during stress testing began in the early 1960s.^{11,12} Signals were recorded using FM tape recorders and processed off-line. Subsequent increase in computer processing power allowed ST segments to be analyzed on-line and various mathematical constructs such as "negative ST integral" and "ST amplitudes" to be calculated. (see Computer algorithms in automated ST analysis).

The use of ECG during anaesthesia was introduced initially for the monitoring of dysrhythmias. The earliest reports were on its use in animals during chloroform anaesthesia.^{13,14} In 1960, the first large clinical report on intraoperative ECG monitoring appeared, emphasizing the detection of dysrhythmias using lead II.¹⁵ It was not until 1976 that V_5 was advocated for intraoperative ischaemia monitoring.¹⁶

In 1979, computerized ST analysis was introduced to the operating room using an exercise ECG system.¹⁷ Subsequent anaesthesia monitors allowed simultaneous ST monitoring and trending in three orthogonal leads, e.g., $-V_1$, AVF, and V_5 .¹⁸ With its simplicity, the use of automated ST analysis is appealing and has become routine.

The ECG signal

Signal acquisition

Monitoring the ECG in the operating room requires signal acquisition of the order of millivolts in an environment fraught with electrical interference, i.e., 60 Hz alternating current, cautery radiofrequency, motion artifacts etc. To improve the signal, skin cleansing with alcohol and mild superficial abrasion with fine sandpaper help to reduce skin impedance from 100,000 Ω to 5,000 Ω or less.¹⁹ In addition, to filter out the interference, a frequency bandwidth of 0.5 to 40 Hz is used. This "monitoring" mode affects a monitor's response to low frequency signals such as the ST segments considerably and may result in false ST depression.²⁰ In order to perform ST segment analysis, the diagnostic or extended mode should be used, with a frequency

response of 0.05 to 60 or 100 Hz. Usually, monitors capable of on-line ST segment analysis do so automatically in the diagnostic mode although the ECG display may still be in the monitoring mode. Caution must be exercised if the ST segment is analyzed visually, especially if the diagnostic mode has to be switched on manually or is not available as in some older monitors.

Before ST analysis, an analogue-to-digital (A-D) conversion of ECG signal is performed. The digital sampling rate must be ≥ 256 Hz. Lower sampling frequencies can leave gaps in the digital signal and produce errors in subsequent analysis. To provide high resolution ECG, some monitors sample at 1000 Hz.

Signal processing

After a sampling interval or epoch, a digital QRS complex is obtained. The quality is proportional to the square root of the number of heart beats averaged, usually 9 to 25. Sampling time may be too long if more beats are averaged. Baseline reference points, fiducial points, are determined mathematically using the point of most rapid amplitude change, usually the downslope of a R wave.

Individual epochs may be corrupted by artifacts. After establishing a baseline QRS template, subsequent beats are aligned using fiducial points; artifacts and abnormal beats, i.e., extrasystoles, are rejected. To improve the template, subsequent beats are incorporated by signal averaging, of which "incremental averaging" is probably the best known: each time-aligned point on a new cardiac cycle is compared with its corresponding member in the current average. Whenever the average is different, it is incremented or decremented by a small, fixed amount of 3.5 μV .

Signal distortion

For each epoch, a representative QRS complex is generated by the computer, usually a median of the QRS complexes during the epoch. Distortion is a concern since ST analysis is usually based on the median complex and not on individual beats. In one study, the accuracy was examined in 17 patients admitted to a coronary care unit.²¹ The ST_{60} , defined as the amount of ST depression measured 60 msec from the J point (see Figure 1), was calculated on-line by the monitor, and compared with off-line calculations based on 250 Hz A-D conversion with one manually selected beat per minute. Serious errors by the monitor occurred in three patients due to aberrant QRS morphology, i.e., widened QRS, PVC etc. After excluding those patients, the monitor's margin of error was within 0.5 mm for 92% of the remaining data sets.

In a study of 43 patients in exercise stress testing, two

FIGURE 2 Two examples of computer-generated errors in ST analysis. The minimal, maximal, and most recent ST segments as documented by the monitor are illustrated. Above each QRS complex is the amount of ST deviation noted by the monitor. In Figure 2a, there is 2.96 mm ST depression although the excessive baseline shift would make analysis difficult. In Figure 2b, the marker for the reference point is buried in the QRS complex. The result is that the point of measurement, 80 msec after the J point, is depressed by 3.68 mm.

computerized systems with on-line analysis were compared: an ambulatory monitor and an exercise ECG system.²² The criterion for the ambulatory monitor was ≥ 1 mm of downsloping or horizontal ST depression for ≥ 40 sec; ST_{60} was measured on the exercise ECG system. Compared with the exercise ECG system, there were seven false positives and three false negatives in the ambulatory monitor. Sensitivity and specificity were 83% and 72% respectively, while the positive and negative predictive values were 68% and 86% respectively. Although four of the misdiagnoses were due to excessive baseline shifts, no identifiable reason was noted for the other errors.

These studies illustrate that QRS recognition in on-line computerized ST analysis is not foolproof. In order to avoid misdiagnosis, the need to visually confirm computer diagnosis cannot be overemphasized. In Figure 2, two examples of computer errors during intra-operative monitoring are shown.

The extent of signal distortion may differ in different ECG systems. In one study, 109 patients undergoing coronary artery bypass surgery were followed.²³ The incidence of myocardial ischaemia was documented using five ECG systems simultaneously: an operating room monitor with a bandwidth of 0.5–30 Hz, a second monitor at 0.05–125 Hz, a standard twelve-lead ECG at 0.05–40 Hz and at 0.05–100 Hz, and an AM Holter recorder. The ECG printouts from each system were independently analyzed by three individuals and ischaemia was defined as ≥ 1 mm horizontal/downsloping ST depression or ≥ 1 mm ST elevation 60 msec after

the J point. The incidence of ischaemia upon arrival in the operating room and after induction of anaesthesia ranged from 4.6 to 15.6% and 8.3 to 27.5% respectively, depending on the system used. The problem of diagnosing "ischaemia" when different ECG systems are used is highlighted in this study.

ST depression

Criteria for ST depression

The classical criteria for ischaemia have been ≥ 1 mm horizontal or downsloping ST depression. However, in a six year follow-up of 438 patients after exercise stress testing, the incidence of coronary events was 13% in patients with 2 mm downsloping ST depression, 9% with 2 mm horizontal ST depression, and 9% with 2 mm upsloping ST depression at 0.08 second after the J point.²⁴ Since the incidence is comparable, upsloping ST depression has been accepted by some as another criterion for ischaemia.

It must be emphasized that the study above was conducted using CM_5 , a bipolar lead (see ECG systems). There are no long term follow-up studies on the validity of slowly upsloping ST depression in standard twelve-lead ECG. In studies comparing exercise stress testing with coronary angiography, upsloping segments improved sensitivity marginally but incurred more false positives.^{25,26} The discrepancy may be explained partly by using standard ECG leads versus bipolar leads. Generally, upsloping ST depression as a diagnostic criterion will increase the false positive rate.

Computer algorithms for automated ST analysis

To emulate visual analysis, many algorithms have been developed for ST analysis in exercise stress testing. One of the earliest was the "ST index": the numerical sum of mean ST depression at 60–70 msec after the peak R wave, and ST slope at 70–90 msec after the peak R wave. Values ≤ 1 mm during maximal treadmill exercise were considered indicative of coronary artery disease.²⁷ Later, "negative ST integral" was suggested,²⁸ calculated as the area-under-the-curve for ST depression starting from the J point to the crossing of the baseline, essentially a time-voltage integral. Values ≥ 7.5 μ v-sec during exercise were considered indicative of coronary artery disease. More recently, ST indexed to heart rate has been suggested but more critical studies have shown conflicting results.²⁵

One algorithm is the ST amplitude, a voltage measurement of ST depression. If measured at the J point, serious errors may occur, especially in normal individuals; at 60 or 80 msec after the J point, i.e., ST_{60} or ST_{80} , the results are more accurate and seem to be compara-

ble.²⁹ In one study, ST_{60} was equal to or better than the ST integral or ST/heart rate index in diagnosing coronary artery disease.³⁰

Monitoring ST depression in the operating room

The most common measurement in anaesthesia monitors is ST_{60} or ST_{80} . However, the various algorithms proposed in exercise stress testing have not been critically evaluated or compared in the operating room environment. Most anaesthesia monitors also do not distinguish upsloping from downsloping or horizontal ST depression. In the presence of artifacts and computer errors, however, most anaesthesia monitors allow the user to adjust the point of measurement on the PR and ST segments as well as the J point. Currently, there are few guidelines or standards to govern the accuracy and performance of computerized ST monitors in the operating room. In fact, few monitors with on-line ST analysis have been subjected to peer-reviewed evaluation in the operating room.

ECG systems and the measurement of ST depression

Skin preparation and electrode placement affect the quality of ECGs. An example is the placement of limb electrodes on the torso to reduce motion artifacts during exercise stress testing.⁹ The "RA" and "LA" electrodes are moved to the ipsilateral infraclavicular fossa medial to the deltoid muscle. The "LL" electrode is moved to a point halfway between the costal margin and the left iliac crest along the anterior axillary line. Although initial studies did not show any compromise in reliability, discrepancies have since been reported, including erroneous absence or presence of Q waves and axis shift.³¹ Although ST segment changes are rarely described, the placement of electrodes may have an impact on the ECG and its interpretation intraoperatively.

Variation in ST segments may occur with the use of bipolar leads, i.e., CS_5 , CC_5 , and CM_5 (Figure 3). Although the responses in V_5 and CC_5 during stress testing are similar, there is less horizontal or downsloping but more upsloping ST depression in CM_5 .³² This may help to explain why upsloping ST depression in CM_5 is a valid diagnostic criterion for coronary artery disease.²⁴ Using CS_5 , however, sensitivity and specificity were changed from 64 to 76% and 93 to 82% respectively when slowly upsloping ST depressions were included.²⁶ During exercise stress testing, occasionally, twelve-lead ECG was positive when simultaneous recordings of CC_5 and CM_5 were negative, and vice versa,³³ suggesting that bipolar leads respond differently from standard ECG leads.

Although bipolar leads have been advocated in the operating room, a study comparing QRS deflections in

FIGURE 3 Illustration of bipolar leads. "5" denotes the emulation of V_5 precordial lead. (+) and (−) denote the LA and RA electrodes respectively in a three-lead ECG system. The LL electrode is placed as usual and the system set to lead I. The LA electrode is placed at the left 5th intercostal space, anterior axillary line. With CS_5 , RA is placed at the right midinfraclavicular region; with CM_5 , at the manubrium; with CC_5 , at the right 5th intercostal space, anterior axillary line; and with CB_5 , at the right midscapular region.

V_5 and CB_5 noted greater ST depression in the bipolar lead, mean values being 0.3–0.4 mm higher.³⁴ In another study, CS_5 and CB_5 exhibited 0.3–0.7 mm more ST depression than V_5 .³⁵ Whether the prognosis of intraoperative ST depressions in bipolar leads versus traditional leads are similar is unknown. The threshold for significance in intraoperative upsloping ST depressions is also unclear.

False positives and false negatives in ST analysis

As a predictor for the site of myocardial ischaemia, ST depression is poor. In a retrospective study, patients with single-vessel coronary artery disease were studied.³⁶ The ECG during myocardial infarction (MI), angina, or exercise stress test were reviewed. The location of arterial narrowing was predicted in 91% of patients by ST elevations, in 84% by T-wave inversions, but in only 60% by ST depression.

Myocardial ischaemia does not always result in ST changes. During angioplasty, ECG changes were correlated with the site of balloon occlusion.³⁷ In 84% of left anterior descending occlusions and in 92% of right coronary occlusions, ST elevation was observed. However, elevation was seen in only 32% of left circumflex occlusions. Of patients with left circumflex occlusion, 47% did not show any ST changes.

In the operating room, false negatives also occur frequently. In one study, haemodynamic variables, myocardial lactate production, and ST segment changes were correlated in 29 patients undergoing coronary artery revascularization.³⁸ Although open to debate, myocardial ischaemia was presumed to be present when myocardial lactate production was detected. In that setting, Holter monitoring with V₂, V₅, and AVF had a sensitivity of 1.6% and specificity of 100% while strip chart recording using II and V₅ had a sensitivity of 17.5% and specificity of 87.7%. The strip chart was recorded at a frequency bandwidth of 0.5–40 Hz and therefore the incidence of ST depression may have been overestimated. The study population would have a high prevalence and severity of coronary artery disease. Therefore, the results may not be directly applicable to the non-cardiac surgical population.

Many factors cause ST depression without myocardial ischaemia. Digoxin, hypokalaemia, and motion artifacts are known to cause ST depression. Other causes, such as hypothermia, positional changes, and tachycardia, occur frequently in the perioperative period. During exercise stress testing, J point depression is known to occur but may be a result of tachycardia. In one study of caesarean section under spinal anaesthesia, altered cardiac sympathetic tone was thought to be the cause of ST depression.³⁹ Depression of the ST segment has also been described with hyperventilation.⁴⁰

Abnormal resting ECG with ST-T wave abnormalities make ST depression more difficult to interpret. Conduction defects such as left bundle branch block and Wolff-Parkinson-White syndrome alter repolarization and may lead to erroneous ST shifts. Left ventricular hypertrophy with strain also alters repolarization, resulting in false positive ST depression. Finally, the presence of right bundle branch block decreases the sensitivity and specificity of exercise ST depression in the diagnosis of coronary artery disease.^{41,42}

Epidemiology

Epidemiological definitions

In the operating room, ST analysis is used as a diagnostic tool for detecting myocardial ischaemia and/or infarction. The usefulness of a diagnostic test is deter-

TABLE

Test	"Gold Standard" test		
	Disease positive	Disease negative	
Positive	TP	FP	PPV = TP/(TP + FP)
Negative	FN	TN	NPV = TN/(TN + FN)
	Sensitivity = TP/(TP + FN)	Specificity = TN/(TN + FP)	

TP: True Positive; FN: False Negative; PPV: Positive Predictive Value; FP: False Positive; TN: True Negative; NPV: Negative Predictive Value.

mined by its accuracy, an objective comparison between the test and a reference test or "gold standard." The existence of disease in patients is defined by the "gold standard." Sensitivity is then calculated as the proportion of patients with the disease correctly identified by the test. Specificity is the proportion of patients without the disease correctly identified by the test (Table). Positive predictive value is the likelihood of having the disease when tested positive. Negative predictive value is the likelihood of not having the disease when tested negative. If the disease prevalence decreases from one test population to another, the positive predictive value decreases while the negative predictive value increases. In certain circumstances, when a test is transposed from a high to a low prevalence population, the sensitivity and specificity may also change, especially if the severity of disease in the population changes. Finally, in order to avoid "incorporation bias," the "gold standard" should be independent of the diagnostic test in defining its accuracy.⁴³ An in-depth discussion of these concepts is beyond the scope of this article and is well reviewed elsewhere.^{44–46}

Epidemiology of exercise stress testing

Much of the work on establishing the validity of ST segment deviation in diagnosing coronary artery disease was performed in exercise stress testing. Similarly, computerized ST segment analysis was initially developed for use in the exercise stress test setting.

Using coronary angiography as the "gold standard," the sensitivity of ST segment depression in predicting coronary artery disease is 50% to 78% and the specificity 70% to 95%.^{8,10,25,26,30,33} In general, a diagnostic test with a high specificity is better for ruling-in disease. Conversely, a diagnostic test with a high sensitivity is better for ruling-out disease.⁴⁷ Hence, ST depression during exercise stress testing is generally a much better test for ruling-in coronary artery disease when positive than for ruling-out disease when negative.

As the anatomical severity of disease diminishes, i.e., triple vessel or left main coronary artery disease versus single vessel disease, the sensitivity of exercise ST depression in predicting coronary artery disease also decreases, to about 40%.^{8,25,26} When disease prevalence decreases, as in the screening of asymptomatic subjects, the positive predictive value was 43% for coronary artery stenosis $\geq 50\%$.⁴⁸ In another study, 2500 asymptomatic male aviators underwent exercise testing with 55 abnormal results.⁴⁹ Using thallium scintigraphy, echocardiography, and ambulatory ECG, nine of the 55 were diagnosed as having cardiac disease, giving a positive predictive value of 16%! The specificity was not calculated. Overall, exercise ECG has not been found to be useful as a screening tool.

The degree of ST depression may indicate the severity of coronary artery disease. In one study, of the 26 patients with ST depression ≥ 3 mm, three-vessel disease was present in 18 (69%) and proximal lesions of the left anterior descending artery in 24 (92%).⁵⁰ In another study, exercise ST responses were correlated with angiography in 436 patients.⁵¹ Thirty-five patients had left main disease and 89 had three-vessel disease but normal left main. The combination of downsloping ST depression ≥ 2 mm, early in the test, lasting ≥ 6 min. into recovery, or extending into ≥ 5 ECG leads were 74% predictive of either left main or three-vessel disease. The sensitivity was 49%. The same criteria had a sensitivity of 74% and predictive value of 32% for isolated left main disease. Specificities were not calculated. The usefulness of a diagnostic test depends on its sensitivity and specificity. Although predictive values are important, they change as disease prevalence changes. Using those criteria to diagnose either left main or three-vessel disease would lead to many false negatives. To diagnose isolated left main disease, the same criteria would lead to many false positives. Without knowing the specificity, it is difficult to make conclusions on the diagnostic accuracy. Nevertheless, when seen clinically, it would seem prudent to be alert to the possibility of left main or three-vessel disease.

Computerized ST analysis is generally accepted to be useful although most studies demonstrating its improvement over visual interpretation contain only a small number of patients. In a larger study, computerized analysis increased sensitivity by about 30%, with a decrease in specificity of about 5%, over visual interpretation.⁵² In another study, 107 patients without previous MI were referred for investigation of chest pain and exercise stress testing.⁵³ The sensitivities of computerized ST analysis and visual interpretation were 59 and 58% respectively; the specificities were 92 and 88% respectively. More recently, in 271 patients without pre-

vious MI, exercise stress testing was performed within 24 hr of coronary angiography.⁵⁴ Computerized analysis and visual interpretation were compared in a blinded fashion. Sensitivities of computer and visual analysis were 51% and 51% respectively, at a specificity level of 87%. Receiving operating curves were not different. Overall, the accuracy of computerized analysis seems to be no worse than visual interpretation, but is not necessarily better.

Epidemiology of intraoperative ST depression

Although useful to review, the epidemiological data in exercise stress testing can only be transposed to the operating room environment with caution. There are major differences between the application of ST segment analysis in anaesthesia and in exercise stress testing. The anaesthetist strives to maintain a balance between myocardial oxygen supply and demand. The anaesthetic goals of ST monitoring are to diagnose myocardial ischaemia and/or infarction early in the process, and to be able to institute therapeutic interventions to reduce the incidence or extent of perioperative infarction. In exercise stress testing, one attempts to induce an imbalance of myocardial oxygen supply and demand. Major confounders affecting its diagnostic accuracy are $\dot{V}O_2$ and heart rate, both of which are frequently modified during anaesthesia. Therefore, the diagnostic accuracy of ST depression during exercise stress testing may be different in the operating room.

The ability of different combinations of ECG monitoring leads to emulate eight- or twelve-lead ECG has been studied.^{55,56} Combining II, V_4 , V_5 , or I, II, V_5 yields a sensitivity of 96–100%. Combining II and V_5 yields a sensitivity of only 80%. "Sensitivity" here refers to the proportion of ST depression on multi-lead ECG detectable on two or three-lead ECGs; it does not refer to the accuracy in diagnosing intraoperative myocardial ischaemia. If one considers that eight- or twelve-lead ECG does not detect all ischaemic episodes, the diagnostic accuracy is reduced further.

The accuracy of computerized ECG in the electrically "unfriendly" operating room is not well studied. In a study on intraoperative myocardial ischaemia, two ST monitors were compared.⁵⁶ One monitor used leads II and V_5 while the other, leads I, II, and V_5 . Using visual interpretation of eight-lead ECG printouts as the "gold standard," the sensitivities of the two monitors were 75% vs 100% and the specificities were 69% vs 50%. The positive predictive values were 35% vs 36% and the negative predictive values were 93% vs 100%. Over 60% of ST changes on the monitors were not seen on ECG printouts. It is not known if the results are partly

due to using only eight leads. Nevertheless, the difference between computerized on-line analysis and ECG printouts may be significant.

In the operating room, off-line computerized ST analysis seems to be better than visual analysis due largely to the ability to measure each recorded ECG complex. Another advantage of off-line analysis is the ability to manually exclude artifacts and abnormal beats such as ventricular ectopies. In one study, 332 men undergoing noncardiac surgery were monitored using a two-lead AM Holter recorder and analyzed off-line.⁵⁷ Myocardial ischaemia was noted in 26% of patients, whereas only 2% were identified intraoperatively by the anaesthetist. These results were confirmed in a subsequent study.⁵⁵ However, in the operating room, on-line, real time ST analysis, is more relevant to clinicians. As alluded to above, on-line ST analysis does not allow the manual exclusion of artifacts and abnormal beats. There are few data to confirm that on-line computerized ST analysis is better than visual analysis. Ever-present is the concern of signal distortion and the incorporation of abnormal beats in the computer analysis. Nevertheless, the anaesthetist does have the ability to reset the computer when obvious errors occur. Given the number of anaesthetic tasks in the operating room, automated trending can be invaluable in providing on-going ST monitoring, provided one is vigilant to the potential of computer errors.

Not all patients with risk factors for coronary artery disease have the disease. Similarly, the disease severity of patients with coronary artery disease is not uniform. Without knowing the number of patients with single vessel versus multiple vessel coronary artery disease, it is difficult to transfer results from one study to another. The sensitivity of ST depression in diagnosing myocardial ischaemia in an exercise stress test is significantly affected by the severity of coronary artery disease. In the setting of intraoperative monitoring, when ST segment monitoring is applied to the general population, with likely a low prevalence of coronary artery disease, the diagnostic accuracy for myocardial ischaemia is unknown. Based on the studies in exercise stress testing, a cautious speculation would be that the accuracy and, more relevant to the anaesthetist, the positive predictive value would be extremely low.

Impact of ST monitoring on postoperative outcome

In one study, intraoperative TEE, twelve-lead ECG, and two-lead ECG were correlated. The sensitivities of each of the modalities in identifying postoperative ischaemic outcomes were 27, 27, and 50% respectively.⁵⁷ Interestingly, the criteria for diagnosing ischaemia in the twelve-lead and two-lead ECGs were different, and

explain in part the better sensitivity of the two-lead ECG. Postoperative ischaemic outcomes were defined as cardiac death, nonfatal MI, and unstable angina. The positive predictive values for the outcomes were 6, 7, and 7% respectively.

In another study, among 1487 men older than 40 yr undergoing major, nonemergency, noncardiac operations, the overall incidence of perioperative MI was 1.7%.⁵⁸ Patients were stratified into "high risk," with clinical or laboratory evidence of coronary artery disease; "intermediate risk," with peripheral vascular disease but no evidence of coronary artery disease; "low risk," with risk factors for atherosclerosis but no evidence of vascular disease; and "no risk," with no risk factors or disease. In the "high risk" group, the incidence of MI was 4.1%. The incidence in the "intermediate risk" group was 0.8%. The incidence in "low risk" and "no risk" groups was 0%. In total, there were 15 MIs in 1487 operations. In the context of preventing postoperative MI, therefore, only a very small proportion of patients benefit from ST monitoring. In addition, as noted above, the low positive predictive value of intraoperative ST changes may falsely identify a high proportion of surgical patients at increased risk for postoperative ischaemic events such as MI, cardiac death, and unstable angina. The cost implications for false positives may be considerable.⁵⁹

For ST monitoring to be useful, one must show that intraoperative myocardial ischaemia predicts perioperative cardiac events, and that early detection allows interventions to alter the morbidity. In fact, earlier studies seemed to show that perioperative myocardial ischaemia led to higher cardiac mortality and morbidity.⁶⁰⁻⁶⁴ One of the earliest studies emphasized the importance of controlling myocardial oxygen demand.⁶⁵ Other studies emphasized the potential of preventing ischaemia by measures such as prophylactic β -blockade⁶⁶ or intravenous nitroglycerin.⁶⁷ However, in a study of perioperative ischaemia on one hundred patients, the incidence of pre, intra, and postoperative ischemia were 28, 27, and 42% respectively.⁶⁸ More recent studies show a lack of correlation between intraoperative haemodynamics and myocardial ischaemia.^{69,70} In a large study of elective noncardiac surgical population, 474 male patients with, or at high risk for, coronary artery disease were prospectively followed.⁷¹ Multivariate analysis failed to find any association between intraoperative ischaemia and postoperative ischaemic outcomes, defined as cardiac death, MI, and unstable angina. Ischaemia in the postoperative period, however, was associated with a 2.8 fold increase in odds for all adverse cardiac outcomes and a 9.2 fold increase in odds for an ischaemic event.

Summary

Automated ST monitoring can be an useful tool in anaesthesia. It allows monitoring of ST segments in two or more leads simultaneously and has the capability to alert the anaesthetist with even minor ST depression. Computerization also makes the task of ST monitoring less onerous. However, in order to utilize the technology well, one must know its reliability and limitations.

When intraoperative ST depression occurs, the diagnostic accuracy of ST depression in exercise stress testing cannot be assumed. One must be vigilant to the potential of computer errors and the frequent occurrence of factors resulting in false positives. For most monitors, ST depression of 0.5 mm is well within the margin of error and likely have little diagnostic importance. Based on the results in stress testing, ST depression ≥ 2 mm, affecting multiple areas, associated with hypotension and prolonged duration, may be indicative of left main or three-vessel disease. Also, one must be vigilant to the occurrence of false negatives and not be lulled into a false sense of reassurance when intraoperative ST depression is not seen.

Monitoring of ST segments should be considered within the context of patient population and disease prevalence. As shown in exercise testing of healthy individuals, ST depression is a poor diagnostic criterion when disease prevalence is low. Therefore, applying ST monitoring in the general surgical population may lead to a low predictive value. In applying ST monitoring, the hope is to decrease the incidence of postoperative morbidity, mainly MI, unstable angina, and cardiac death. However, studies to date have not shown that intraoperative ischaemia is a predictor of postoperative cardiac morbidity. These postoperative events are low incidence events and, at best, ST monitoring will affect only a small number of patients. The poor positive predictive value of ST depression may lead to misdiagnosis, with considerable morbidity and cost implications. Computerization and automation of ST analysis will not resolve these underlying epidemiological issues and may, in fact, obscure the pitfalls of ST analysis itself.

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References

- 1 Vincent GM, Abildskov JA, Burgess MJ. Mechanisms of ischemic ST-segment displacement. Evaluation by direct current recordings. *Circulation* 1977; 56: 559-66.
- 2 Bousfield G. Angina pectoris: changes in electrocardiogram during paroxysm. *Lancet* 1918; 2: 457-8.
- 3 Feil H, Siegel ML. Electrocardiographic changes during attacks of angina pectoris. *Am J Med Sci* 1928; 175: 255-60.
- 4 Wood FC, Wolferth CC. Angina pectoris. The clinical and electrocardiographic phenomena of the attack and their comparison with the effects of experimental temporary coronary occlusion. *Arch Int Med* 1931; 47: 337-65.
- 5 Katz LN, Landt H. The effect of standardized exercise on the four-lead electrocardiogram. Its value in the study of coronary disease. *Am J Med Sci* 1935; 189: 346-51.
- 6 Master AM, Jaffe HL. The electrocardiographic changes after exercise in angina pectoris. *J Mt Sinai Hosp NY* 1941; 7: 629-32.
- 7 Blackburn H, Katigbak R. What electrocardiographic leads to take after exercise? *Am Heart J* 1964; 67: 184-5.
- 8 Sketch MH, Nair CK, Esterbrooks DJ, Mohiuddin SM. Reliability of single-lead and multiple-lead electrocardiography during and after exercise. *Chest* 1978; 74: 394-401.
- 9 Mason RE, Likar I. A new system of multiple-lead exercise electrocardiography. *Am Heart J* 1966; 71: 196-205.
- 10 Mason RE, Likar I, Biern RO, Ross RS. Multiple-lead exercise electrocardiography. Experience in 107 normal subjects and 67 patients with angina pectoris, and comparison with coronary cinearteriography in 84 patients. *Circulation* 1967; 36: 517-25.
- 11 Blomqvist G. The Frank lead exercise electrocardiogram. A quantitative study based on averaging technic and digital computer analysis. *Acta Med Scand* 1965; 178 (Suppl 440): 7-93.
- 12 Bruce RA, Mazzeella JA, Jordan JW Jr, Green E. Quantitation of QRS and ST segment responses to exercise. *Am Heart J* 1966; 71: 455-66.
- 13 Oliver G, Schäfer EA. The physiological effects of extracts of the suprarenal capsules. *J Physiol* 1895; 18: 230-76.
- 14 Levy AG, Lewis T. Heart irregularities, resulting from the inhalation of low percentages of chloroform vapour, and their relationship to ventricular fibrillation. *Heart* 1911; 3: 99-112.
- 15 Cannard TH, Dripps RD, Helwig J Jr, Zinsser HF. The electrocardiogram during anesthesia and surgery. *Anesthesiology* 1960; 21: 194-202.
- 16 Kaplan JA, King SB. The precordial electrocardiographic lead (V₅) in patients who have coronary-artery disease. *Anesthesiology* 1976; 45: 570-4.
- 17 Roy WL, Edelist G, Gilbert B. Myocardial ischemia during non-cardiac surgical procedures in patients with coronary-artery disease. *Anesthesiology* 1979; 51: 393-7.
- 18 Kotrly KJ, Kotter GS, Mortara D, Kampine JP. Intraoperative detection of myocardial ischemia with an

- ST segment trend monitoring system. *Anesth Analg* 1984; 63: 343-5.
- 19 *Mirvis DM, Berson AS, Goldberger AL, et al.* Instrumentation and practice standards for electrocardiographic monitoring in special care units. *Circulation* 1989; 79: 464-71.
 - 20 *Berson AS, Pipberger HV.* The low-frequency response of electrocardiographs, a frequent source of recording errors. *Am Heart J* 1966; 71: 779-89.
 - 21 *Burns MP, Downs WG.* Clinical evaluation of a bedside ST-segment monitor. *Computers in Cardiology Proceedings*. Washington, DC. IEEE Computer Society Press. 1989; 97-100.
 - 22 *Jamal SM, Mitra-Duncan L, Kelly DT, Freedman SB.* Validation of a real-time electrocardiographic monitor for detection of myocardial ischemia secondary to coronary artery disease. *Am J Cardiol* 1987; 60: 525-7.
 - 23 *Slogoff S, Keats AS, David Y, Igo SR.* Incidence of perioperative myocardial ischemia detected by different electrocardiographic systems. *Anesthesiology* 1990; 73: 1074-81.
 - 24 *Stuart RJ Jr, Ellestad MH.* Upsloping S-T segments in exercise stress testing. Six year follow-up study of 438 patients and correlation with 248 angiograms. *Am J Cardiol* 1976; 37: 19-22.
 - 25 *Morise AP, Duval RD.* Accuracy of ST/heart rate index in the diagnosis of coronary artery disease. *Am J Cardiol* 1992; 69: 603-6.
 - 26 *Goldschlager N, Selzer A, Cohn K.* Treadmill stress tests as indicators of presence and severity of coronary artery disease. *Ann Int Med* 1976; 85: 277-86.
 - 27 *McHenry PL, Stowe DE, Lancaster MC.* Computer quantitation of the ST-segment response during maximal treadmill exercise. Clinical correlation. *Circulation* 1968; 38: 691-701.
 - 28 *Sheffield LT, Holt JH, Lester FM, Conroy DV, Reeves TJ.* On-line analysis of the exercise electrocardiogram. *Circulation* 1969; 40: 935-44.
 - 29 *Okin PM, Bergman G, Kligfield P.* Effect of ST segment measurement point on performance of standard and heart rate-adjusted ST segment criteria for the identification of coronary artery disease. *Circulation* 1991; 84: 57-66.
 - 30 *Ribisl PM, Liu J, Mousa I, et al.* Comparison of computer ST criteria for diagnosis of severe coronary artery disease. *Am J Cardiol* 1993; 71: 546-51.
 - 31 *Kleiner JP, Nelson WP, Boland MJ.* The 12-lead electrocardiogram in exercise testing. A misleading baseline? *Arch Intern Med* 1978; 138: 1572-3.
 - 32 *Froelicher VF Jr, Wolthius R, Keiser N, et al.* A comparison of two bipolar exercise electrocardiographic leads to lead V5. *Chest* 1976; 70: 611-6.
 - 33 *Chaitman BR, Bourassa MG, Wagniat P, Corbara F, Ferguson RJ.* Improved efficiency of treadmill exercise testing using a multiple lead ECG system and basic hemodynamic exercise response. *Circulation* 1978; 57: 71-9.
 - 34 *Bazara MG, Norfleet EA.* Comparison of CB₅ and V₅ leads for intraoperative electrocardiographic monitoring. *Anesth Analg* 1981; 60: 849-53.
 - 35 *Griffin RM, Kaplan JA.* Comparison of ECG leads V₅, CS₅, CB₅, and II by computerized ST segment analysis. *Anesth Analg* 1986; 65: S65.
 - 36 *Fuchs RM, Achuff SC, Grunwald L, Yin FCP, Griffith LSC.* Electrocardiographic localization of coronary artery narrowings: studies during myocardial ischemia and infarction in patients with one-vessel disease. *Circulation* 1982; 66: 1168-76.
 - 37 *Berry C, Zalewski A, Kovach R, Savage M, Goldberg S.* Surface electrocardiogram in the detection of transmural myocardial ischemia during coronary artery occlusion. *Am J Cardiol* 1989; 63: 21-6.
 - 38 *Hall RI, O'Regan N, Gardner M.* Detection of intraoperative myocardial ischaemia - a comparison among electrocardiographic, myocardial metabolic, and haemodynamic measurements in patients with reduced ventricular function. *Can J Anaesth* 1995; 42: 487-94.
 - 39 *Eisenach JC, Tuttle R, Stein A.* Is ST segment depression of the electrocardiogram during cesarean section merely due to cardiac sympathetic block? *Anesth Analg* 1994; 78: 287-92.
 - 40 *Lary D, Goldschlager N.* Electrocardiographic changes during hyperventilation resembling myocardial ischemia in patients with normal coronary arteriograms. *Am Heart J* 1974; 87: 383-90.
 - 41 *Tanaka T, Friedman MJ, Okada RD, Buckels LJ, Marcus FI.* Diagnostic value of exercise-induced S-T segment depression in patients with right bundle branch block. *Am J Cardiol* 1978; 41: 670-3.
 - 42 *Yen RS, Miranda C, Froelicher VF.* Diagnostic and prognostic accuracy of the exercise electrocardiogram in patients with preexisting right bundle branch block. *Am Heart J* 1994; 127: 1521-5.
 - 43 *Ransohoff DF, Feinstein AR.* Problems of spectrum and bias in evaluating the efficacy of diagnostic tests. *N Engl J Med* 1978; 299: 926-30.
 - 44 *Sackett DL, Haynes RB, Tugwell P.* The selection of diagnostic tests. In: *Clinical Epidemiology*, 1st ed. Boston/Toronto: Little, Brown and Company, 1985: 47-57.
 - 45 *Dupuis J-Y, Nathan HJ, Wynands JE.* Clinical application of cardiac risk indices: how to avoid misleading numbers. *Can J Anaesth* 1991; 38: 1055-64.
 - 46 *Goldman L.* Cardiac risk in noncardiac surgery: an update. *Anesth Analg* 1995; 80: 810-20.
 - 47 *Sackett DL, Haynes RB, Tugwell P.* The interpretation of diagnostic data. In: *Clinical Epidemiology*, 1st ed. Boston/Toronto: Little, Brown and Company, 1985: 59-138.

- 48 *Froelicher VF Jr, Yanowitz FG, Thompson AJ.* The correlation of coronary angiography and the electrocardiographic response to maximal treadmill testing in 76 asymptomatic men. *Circulation* 1973; 48: 597-604.
- 49 *Pedersen F, Sandøe E, Lærkeborg A.* Prevalence and significance of an abnormal exercise ECG in asymptomatic males. Outcome of Thallium myocardial scintigraphy. *Eur Heart J* 1991; 12: 766-9.
- 50 *Goldman S, Tselos S, Cohn K.* Marked depth of ST-segment depression during treadmill exercise testing. *Chest* 1976; 69: 729-33.
- 51 *Weiner DA, McCabe CH, Ryan TJ.* Identification of patients with left main and three vessel coronary disease with clinical and exercise test variables. *Am J Card* 1980; 46: 21-7.
- 52 *Simoons ML, Hugenholtz PG.* Estimation of the probability of exercise-induced ischemia by quantitative ECG analysis. *Circulation* 1977; 56: 552-9.
- 53 *Sketch MH, Mohiuddin SM, Nair CK, Mooss AN, Runco V.* Automated and nomographic analysis of exercise tests. *JAMA* 1980; 243: 1052-5.
- 54 *Detrano R, Salcedo E, Leatherman J, Day K.* Computer-assisted versus unassisted analysis of the exercise electrocardiogram in patients without myocardial infarction. *J Am Coll Cardiol* 1987; 10: 794-9.
- 55 *London MJ, Hollenberg M, Wong MG, et al.* Intraoperative myocardial ischemia: localization by continuous 12-lead electrocardiography. *Anesthesiology* 1988; 69: 232-41.
- 56 *Ellis JE, Shah MN, Briller JE, Roizen MF, Aronson S, Feinstein SB.* A comparison of methods for the detection of myocardial ischemia during noncardiac surgery: automated ST-segment analysis systems, electrocardiography, and transesophageal echocardiography. *Anesth Analg* 1992; 75: 764-72.
- 57 *Eisenberg MJ, London MJ, Leung JM, et al.* Monitoring for myocardial ischemia during noncardiac surgery. A technology assessment of transesophageal echocardiography and 12-lead electrocardiography. *JAMA* 1992; 268: 210-6.
- 58 *Ashton CM, Petersen NJ, Wray NP, et al.* The incidence of perioperative myocardial infarction in men undergoing noncardiac surgery. *Ann Intern Med* 1993; 118: 504-10.
- 59 *Partridge BL, Barash PG, London MJ, McCann HA.* Automated ST-segment trending: what does it mean? *J Clin Monit* 1992; 8: 66-73.
- 60 *Ouyang P, Gerstenblith G, Furman WR, Golueke PJ, Gottlieb SO.* Frequency and significance of early postoperative silent myocardial ischemia in patients having peripheral vascular surgery. *Am J Cardiol* 1989; 64: 1113-6.
- 61 *McCann RL, Clements FM.* Silent myocardial ischemia in patients undergoing peripheral vascular surgery: incidence and association with perioperative cardiac morbidity and mortality. *J Vasc Surg* 1989; 9: 583-7.
- 62 *Pasternack PF, Grossi EA, Baumann FG, et al.* The value of silent myocardial ischemia monitoring in the prediction of perioperative myocardial infarction in patients undergoing peripheral vascular surgery. *J Vasc Surg* 1989; 10: 617-25.
- 63 *Frank SM, Beattie C, Christopherson R, Rock P, Parker S, Gottlieb SO.* Perioperative rate-related silent myocardial ischemia and postoperative death. *J Clin Anesth* 1990; 2: 326-31.
- 64 *Raby KE, Barry J, Creager MA, Cook EF, Weisberg ML, Goldman L.* Detection and significance of intraoperative and postoperative myocardial ischemia in peripheral vascular surgery. *JAMA* 1992; 268: 222-7.
- 65 *Slogoff S, Keats AS.* Does perioperative myocardial ischemia lead to postoperative myocardial infarction? *Anesthesiology* 1985; 62: 107-14.
- 66 *Pasternack PF, Grossi EA, Baumann FG, et al.* Beta blockade to decrease silent myocardial ischemia during peripheral vascular surgery. *Am J Surg* 1989; 158: 113-6.
- 67 *Mangano DT, Hollenberg M, Fegert G, et al.* Perioperative myocardial ischemia in patients undergoing noncardiac surgery - I: Incidence and severity during the 4-day perioperative period. *J Am Coll Cardiol* 1991; 17: 843-50.
- 68 *Coriat P, Daloz M, Bousseau D, Fusciardi J, Echter E, Viars P.* Prevention of intraoperative myocardial ischemia during noncardiac surgery with intravenous nitroglycerin. *Anesthesiology* 1984; 61: 193-6.
- 69 *Gordon MA, Urban MK, O'Connor T, Barash PG.* Is the pressure rate quotient a predictor or indicator of myocardial ischemia as measured by ST - segment changes in patients undergoing coronary artery bypass surgery? *Anesthesiology* 1991; 74: 848-53.
- 70 *Urban MK, Gordon MA, Harris SN, O'Connor T, Barash PG.* Intraoperative hemodynamic changes are not good indicators of myocardial ischemia. *Anesth Analg* 1993; 76: 942-9.
- 71 *Mangano DT, Browner WS, Hollenberg M, et al.* Association of perioperative myocardial ischemia with cardiac morbidity and mortality in men undergoing noncardiac surgery. *N Engl J Med* 1990; 323: 1781-8.