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Intraoperative Myocardial Ischemia: Localization by Continuous 12-Lead Electrocardiography

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Based primarily on results obtained during exercise treadmill testing, electrocardiographic (ECG) leads II and V_5 are the suggested optimal leads for detecting intraoperative myocardial ischemia. However, these recommendations have not been validated in this setting using all 12 ECG leads. Accordingly, the authors studied 105 patients with known or suspected coronary artery disease (CAD) undergoing noncardiac surgery with general anesthesia by continuously recording the 12-lead ECG intraoperatively in all patients. The average duration of monitoring was 8.2 ± 2.7 h (mean ± SD). Ischemic episodes (*i.e.*, ≥1-mm horizontal or downsloping ST depression, ≥1.5-mm slowly upsloping ST depression or ≥1.5-mm ST elevation in a non-Q wave lead) occurred in 25 patients (24%). Out of 51 ischemic episodes, 45 involved ST depression alone, and the remaining six involved both ST depression and elevation. ST segment changes occurred in a single lead only in 14 episodes, while multiple leads were involved in 37 episodes. Lead sensitivity was estimated assuming that all ST segment changes were true positive responses. Sensitivity using a single lead was greatest in V_5 (75%) and V_4 (61%), and intermediate in II, V_3, and V_6 (33%, 24%, and 37%, respectively). The remaining seven leads demonstrated very low sensitivity (2–14%) or exhibited no ischemic changes (I and aV_L). Combining leads V_4 and V_5 increased sensitivity to 90%, while the standard clinical combination, II and V_5, was only 80% sensitive. Sensitivity increased to 96% by combining II, V_4, and V_5. The further addition of V_2 and V_3 (five leads) increased sensitivity to 100%. This study confirms previous recommendations for the routine use of a V_5 lead (either uni- or bipolar) in all patients at risk for ischemia. V_4 is more sensitive than lead II, and should be considered as a second choice. However, lead II, superior for detection of atrial dysrhythmias, is more easily obtained with conventional monitors. The use of all three would appear to be the optimal arrangement for most clinical needs, and is recommended if the clinician has the capability. (Key words: Heart, electrocardiography: coronary artery disease; myocardial ischemia. Monitoring, electrocardiography: computerized analysis; 12 lead.)

PATIENTS WITH CORONARY artery disease (CAD) undergoing surgery, particularly those with previous myocardial infarction, are at increased risk for postoperative myocardial infarction.[1] Many such patients develop electrocardiographic (ECG) evidence of intraoperative myocardial ischemia, a potential risk factor for postoperative infarction.[2] Consequently, it is standard anesthetic practice to monitor all patients with known or suspected CAD for the presence of ischemia.

The recommendations for ECG monitoring of ischemia in the perioperative environment are based primarily on case reports and anecdotal data published over a decade ago.[3–5] These, in turn, were based largely on a single exercise treadmill study demonstrating that 89% of all ischemic changes detected using 12-lead monitoring occurred in V_5.[6] These reports led to adoption of a unipolar or modified (bipolar) V_5 lead as the standard for monitoring ischemia in high-risk patients. Lead II also is anecdotally recommended, for its value in detecting a small percentage of ischemia not present in V_5, as well as its superiority in diagnosing atrial dysrhythmias.[7]

Over the past decade, several factors employed in the design of exercise treadmill studies have allowed better quantitation of sensitivity and specificity of the ischemic ECG response for the detection and prognosis of CAD. These include the use of multiple-lead computerized signal processing, monitoring of the ECG throughout the entire exercise test, and correlation of ECG responses with coronary angiography. These studies have found that monitoring all 12 leads enhances sensitivity approximately 15% (range 4–22%), with only a small decline in specificity (5–8%).[8] Thus, at the present time, most exercise treadmill testing is routinely performed using 12-lead monitoring.

However, the anesthesiologist has little data upon which to base monitoring strategy. Only a few studies have examined the sensitivity of all 12 standard ECG leads in the perioperative setting. Although complete or partial lead sets have been monitored for varying time intervals during cardiac and noncardiac surgery,[9–14] little quantitative data on intraoperative localization of ECG changes have been presented. It may not be possible to extrapolate results obtained during treadmill testing directly to the perioperative environment. In treadmill exercise testing, myocardial ischemia is

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usually precipitated by an increase in myocardial oxygen demand;[15] whereas, during anesthesia and surgery, ischemia may be commonly related to reduction in myocardial oxygen supply due to coronary vasospasm or interference with normal coronary autoregulation.[16] Additionally, differences between patient positioning during surgery and treadmill testing may alter the position of the heart within the thorax. Thus, we sought to determine which leads, or combination of leads, of the standard 12-lead ECG provide maximal detection of ischemic ST-segment changes during the intraoperative period. A microcomputer-augmented ECG system was used to detect significant changes by continuously monitoring all 12 ECG leads in 105 patients with known or suspected CAD undergoing noncardiac surgery with general anesthesia.

Materials and Methods

We studied 105 patients undergoing 108 noncardiac surgical procedures with general anesthesia at the San Francisco Veterans Administration Medical Center. Informed consent was obtained from each patient following approval of the protocol by our institutional review board. Criteria for entry into the study included: 1) known CAD (angina, history of myocardial infarction, or significant Q waves on preoperative ECG), or 2) strongly suspected CAD (patients undergoing vascular surgery, or those with two or more of the following risk factors: hypertension, diabetes, age >70 yr, hypercholesterolemia, or smoking). We excluded patients with left bundle branch block, pacemakers, or a rhythm other than normal sinus or those undergoing thoracic surgery. A resting 12-lead ECG was obtained on the day prior to surgery. Following premedication and entry into the operative holding area, but before entry into the operating room, patients (n = 90) were fitted with ten silver/silver chloride ECG electrodes after vigorous skin preparation (alcohol cleansing and dry sponge abrasion). In the remaining patients, electrodes were applied in the operating room prior to induction of anesthesia. A modified Mason-Likar lead configuration was used, with the leg electrodes placed midway between the anterior and posterior iliac spines.[17] The six precordial leads were carefully placed in the standard positions in all patients.[18] All electrodes and leads were then secured with plastic tape.

The study period began within the first hour before entry into the operating room in most patients, continued throughout surgery in all patients, and ended 30 min to 4 h after arrival in the recovery room or intensive care unit. Monitoring was continuous except during patient transport. A microcomputer-augmented three-channel ECG (MAC II/ST exercise stress system, Marquette Electronics®, Milwaukee, WI) was used to monitor the 12 standard leads. This system digitizes the analog ECG signal at a rate of 500 samples/s. The frequency response is 0.01 Hz to 100 Hz at −3 db. A frequency-based QRS detector classifies incoming ECG complexes, rejecting most artifact such as myographic noise, 60-Hz AC interference, high-frequency electrocautery, and ectopic beats. Accepted QRS complexes are temporally and spatially aligned on a microprocessor template. An incremental averaging algorithm is used to generate what is termed a "median complex," which is recorded for each of the 12 leads every minute at a calibration of 1 mm = 0.1 mv and a paper speed of 25 mm/s, throughout the monitoring period (fig. 1). These median complexes were used for determining ischemic ST segment changes. The digital value of the ST segment position at 60 msec after the J point is recorded along with the median complex. Attending physicians and residents used standard three- or five-lead ECG monitoring systems, and were blinded to the study monitoring system. The anesthesia or recovery room notes were reviewed after surgery for evidence that the clinician had detected ischemia on their monitor. Serial 12-lead ECGs and creatine kinase/lactate dehydrogenase isoenzymes were obtained postoperatively in all patients.

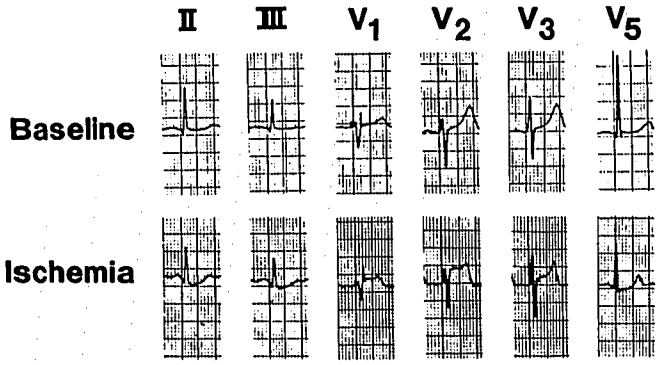

FIG. 1. An ischemic episode involving both ST depression and elevation is illustrated. Median complexes are shown for the pre-induction baseline and during maximum ST elevation. Pronounced ST elevation is present in V_2 (+2.3 mm from baseline) associated with less elevation in the adjacent V_1 and V_3 (+1.0 and +1.5 mm, respectively). Significant ST depression was present in leads II, III, and V_5 (−1.5 mm, −1.5 mm, and −1.0 mm, respectively).

Every median complex recorded during the study period was reviewed by at least two of three investigators (M.G.W., L.L., M.J.L.) after surgery. Positive findings were then reviewed independently by two investigators (M.J.L., M.H.) blinded to the clinical events. When necessary, the accuracy of the ST-segment position was verified using a high-power magnifier. The criteria used for detection of ECG ischemia were: 1) new ST depression (measured 60 msec after the J point) of ≥1 mm in a horizontal or downsloping ST segment; 2)

≥1.5-mm depression in a slowly upsloping ST segment; 3) ST segment elevation ≥1.5 mm from baseline in a non-Q wave lead; or 4) ST elevation ≥1.0 mm if it was simultaneous with ST elevation of ≥1.5 mm in another lead. In the presence of significant resting J point elevation of ≥1 mm above the T-P segment ("early repolarization"), ischemic changes were defined by a decrease to at least ≥0.5 mm below the isoelectric baseline. Required duration of the change was ≥1 min, which is the minimum interval between two recorded median complexes. The ECG recorded at the start of the monitoring period was used as the baseline from which significant changes were calculated, unless the patient was unable to be monitored before entry into the operating room, in which case the ECG obtained the day before surgery was used. When the ECG recorded prior to entry into the operating room differed from the resting 12-lead ECG obtained the day before surgery, the latter was used as the baseline. ST-segment changes occurring during supraventricular or other dysrhythmias were not analyzed.

To facilitate the analysis of ECG data from multiple leads, ST-segment changes were grouped into "ST episodes," which were defined as simultaneous or temporally overlapping ST changes in more than one lead. A change in a single lead only was also classified as an episode. The maximum ST-segment change (in mm) for each lead involved in an episode was also recorded. The duration of an episode was also recorded. The duration of an episode was defined by the time from which the first lead reached its threshold for significance to the time when the last lead in an episode returned to this threshold.

We assumed that all significant responses were true positive responses. The sensitivity of a single lead was calculated as the total number of changes detected in that lead/the total number of episodes detected. The sensitivity of lead combinations was calculated as the total number of episodes in which any lead was positive/the total number of episodes detected.

All data are presented as mean ± standard deviation (SD). Unpaired *t* tests and Chi-square analysis were used where appropriate. Statistical significance was accepted at $P < 0.05$.

Results

The total duration of monitoring for the 108 operations was 883 h (mean = 8.2 ± 2.7 h, range = 2.3 − 15.5 h). Ninety patients were able to be monitored prior to entry into the operating room (mean = 0.4 ± 0.3 h), while 106 patients were monitored postoperatively (mean = 1.8 ± 1.7 h). Twenty-five patients (24%) had 51 ischemic episodes; 17/25 (68%) had only one episode, and 4/25 (16%) had five or more episodes. An example of an ischemic episode is shown in figure 1.

Preoperative Clinical and ECG Characteristics

The clinical characteristics of the study patients are shown in table 1. There were no significant differences found between patients with or without ischemia in any of the clinical variables, except for a higher incidence of preoperative calcium channel blockade in those with ischemia ($P < 0.01$). The predominant anesthetic technique used was isoflurane and nitrous oxide with or without adjuvant opiate. The preoperative ECG (obtained the day before surgery) of eight of the 25 patients with intraoperative ECG changes showed nonspecific resting ST-T wave abnormalities. Five of these patients had changes suggestive, but not diagnostic, of resting preoperative ischemia. Left ventricular hypertrophy was present in four patients, three of whom had resting ST abnormalities; one with right bundle branch block and two with left anterior fasicular hemiblock. One patient with intraoperative ischemia, who was taking digoxin at the time of surgery, was included in the analysis. This patient who developed ST depression in V_5 and V_6, had known CAD (previous inferior myocardial infarction), congestive heart failure (ejection fraction of 35%), and an otherwise normal resting 12-lead ECG. No other patient receiving digoxin (7/105) had a significant ECG change.

Characteristics of Ischemic Episodes

Of the 51 episodes (mean = 2.0 ± 1.8, median = 1.0 episode/patient), two were detected at onset of monitoring, one occurred after arrival in the operating room but before induction of anesthesia, 34 were detected after induction but before extubation, three at extubation but before leaving the operating room, and 11 in the recovery room or intensive care unit. The median duration of the episodes was 10 min, and 31% were <5 min in duration (range 1–177 min). Ischemia was detected by the clinician in only five of the 25 patients.

Forty-five (88%) ischemic episodes involved ST depression in all of the affected leads, while six (12%) episodes involved ST elevation in at least one of the affected leads. ST segment changes occurred in a single lead only in 14 episodes (27%), while multiple leads were involved in 37 episodes (73%) (fig. 2). When more than one lead was involved in a ischemic episode, the leads in which maximal ST change occurred were V_4 (38%) and V_5 (35%), while maximal change was detected in lead II in only 11% of episodes. ST segment positions, at baseline and maximal change, for the individual leads comprising the ischemic episodes are presented in table 2.

The occurrence of ST-segment changes in each of the 12 leads considered individually is shown in figure

TABLE 1. Clinical Data

	Ischemic	Non-ischemic	Total
Preoperative data			
Number of patients	25	80	105
Mean age (yrs)	67 ± 6	65 ± 8	65 ± 7
% of Patients			
Male Sex	100%	98%	98%
Angina	52%	36%	40%
Previous MI	44%	30%	33%
Previous CABG	12%	14%	13%
Hypertension	64%	60%	61%
Diabetes	24%	24%	24%
CHF	16%	14%	14%
Medications			
Nitrates	44%	24%	29%
Beta-adrenergic blocking agents	20%	18%	18%
Calcium-channel blocking agents	36%*	11%	17%
Digoxin	4%	8%	7%
Other anti-hypertensives	28%	20%	22%
Intraoperative data			
Number of operations	25	83	108
Mean duration (min)	338 ± 157	285 ± 151	297 ± 152
% of operations			
Type of Surgery			
Aortic vascular	32%	28%	29%
Carotid endarterectomy	12%	11%	11%
Peripheral revascularization	28%	20%	22%
Intra-abdominal	20%	27%	25%
Other	8%	14%	13%
Type of Anesthesia			
Isoflurane ± opiate/N_2O	76%	63%	66%
Isoflurane ± opiate/O_2	16%	29%	26%
Halothane ± opiate/N_2O	4%	5%	5%
Halothane ± opiate/O_2	—	—	—
High dose opiate/N_2O	4%	1%	2%
High dose opiate/O_2	—	2%	1%

All values were NS by t test or Chi-square except as noted.

* $P < .01$ ischemic *vs.* non-ischemic.

3. This frequency corresponds to the maximal sensitivity for detection of ischemia if that lead alone had been monitored, assuming all ischemic responses were "true positives." Sensitivity of a single lead was greatest for V_5 (75%) followed by V_4 (61%). The sensitivity of leads II, V_3, and V_6 were intermediate (33%, 24%, and 37%, respectively), while the remaining seven leads had either very low sensitivity (2–14% for leads III, aV_R, aV_F, V_1, and V_2) or exhibited no ischemic changes (I and aV_L).

The sensitivity of two-lead combinations was highest for V_4 and V_5 (90%). The standard clinical combination, leads II and V_5, was 80% sensitive, only 5% greater than the use of V_5 alone. Although the addition of V_4 to V_5 substantially increased sensitivity, the addition of V_6 to V_5 did not. Likewise, the use of other inferior leads in addition to lead II were redundant.

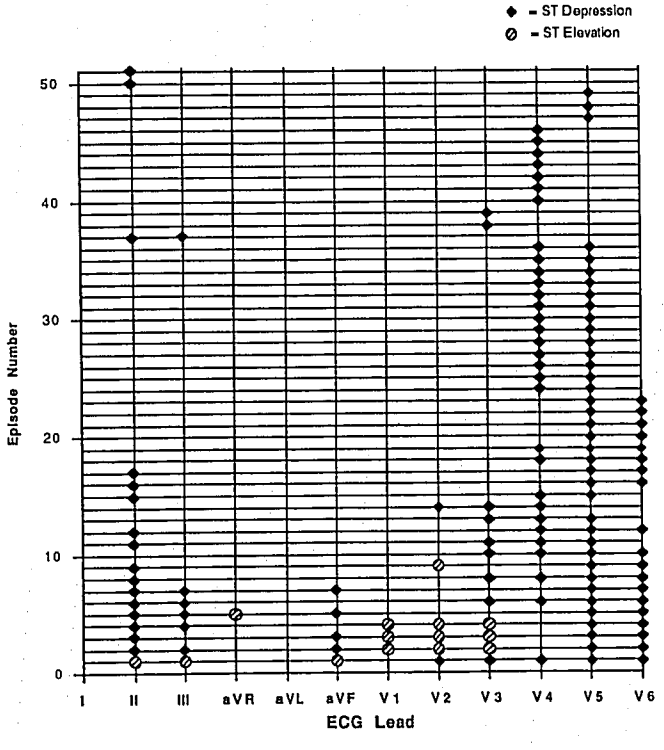

FIG. 2. ST-segment changes (depression and elevation) are grouped into ischemic episodes based on simultaneous or temporally overlapping change. Solitary changes in a single lead were also classified as episodes.

TABLE 2. Mean ST Segment Measurements (mm) at Baseline and at the Maximal Change in Each Lead Comprising an Episode

	II	III	aV_R	aV_F	V_1	V_2	V_3	V_4	V_5	V_6
Baseline ST	−0.2 ± 0.4	−0.3 ± 0.2	0.3 ± 0.0	−0.1 ± 0.4	1.0 ± 1.4	1.5 ± 0.4	0.7 ± 0.8	0.3 ± 0.7	0.0 ± 0.5	−0.2 ± 0.5
Range	−.8/0.1	−.5/0	.3/.3	−.5/.2	0/2.0	1.0/1.9	−0.2/1.8	−0.8/1.6	−1.1/1.0	−1.2/0.5
Patients (n=)	9	4	1	3	2	4	11	19	20	10
Maximal ST segment change Depression	−1.3 ± 0.4	−1.5 ± 0.5		−1.6 ± 0.4		−3.0 ± 0.6	−2.1 ± 0.8	−1.6 ± 0.7	−1.6 ± 0.7	−1.4 ± 0.5
Range	−1/−2.5	−1/−2.2		−1.2/−2.2		−2.6/−3.4	−1.2/−3.6	−1.0/−4.1	−1.0/−3.4	−1.0/−2.5
Episodes (n=)	16	6		4		2	9	31	38	19
Elevation	1.3 ± 0.0	2.0 ± 0.0	1.6 ± 0.0	1.7 ± 0.0	1.9 ± 0.1	2.0 ± 0.4	1.7 ± 0.8			
Range	1.3	2.0	1.6	1.7	1.8/2.0	1.5/2.3	1.0/2.5			
Episodes (n=)	1	1	1	1	3	4	3			

Values presented for maximal change are the relative change from the baseline ST segment measurement. No changes were present in leads I and a V_L.

The sensitivity of three-lead combinations was highest for II, V_4, and V_5 (96%), although substituting V_3 for lead II resulted in similar sensitivity (94%). Using five leads (II, V_2–V_5), all significant changes could be detected, resulting in 100% sensitivity. Thus, the information from any other combinations of leads was redundant.

When ST segment elevation and depression occur simultaneously in adjacent leads during an episode, defining which change is primary or reciprocal is difficult. However, the clinician's perception of its significance might be altered by which change is suspected to be primary. An example of a potentially significant primary change that would have gone undetected by monitoring V_5 alone is shown in figure 1, in which >2-mm ST elevation in V_2 (along with changes in V_1 and V_3), highly suggestive of transmural ischemia in the distribution of the left anterior descending coronary artery,[19] was accompanied by relatively minor ST segment depression in V_5 (less than 1-mm ST depression below the isoelectric baseline in a complex with baseline J point elevation). These changes, undetected by the clinician, occurred in a patient undergoing abdominal aortic aneurysm complicated by hypotension requiring intraoperative inotropic support. Although postoperative myocardial infarction did not occur, the patient developed postoperative congestive heart failure and sustained a major cerebrovascular accident.

Symmetrical T wave inversions were detected in association with ST depression in five episodes. Five additional patients had isolated symmetrical T wave inversions in the absence of ST changes. However, they were not included in the data analysis as the significance of isolated T wave abnormalities in this setting is less well established than that of ST segment changes.[20]

Postoperative myocardial infarction occurred in three patients (one fatal) within 72 h of surgery. All three patients had intra- or early postoperative ST depression. Another patient developed disseminated intravascular coagulation during aortic aneurysm resection. ST depression occurred during this time, and the patient expired in the operating room from progressive hemorrhage.

Discussion

Critique of Methods

The use of a microcomputer-augmented ECG system in this study was based on our need to monitor all 12 leads of the ECG continuously over long periods of time. However, despite widespread clinical use of this technology in both the exercise treadmill setting and routine clinical ECG laboratories, there are potential limitations that could have affected our results.

The median complex we analyzed is a running average of continuously acquired QRS complexes. Thus, it is possible that we may have missed events less than 1 min in duration, the minimum time period between printed median complexes. However, other studies have used similar or shorter durations (as few as three beats).[9,11-12] Our choice, which may have reduced sensitivity (more false negatives), would be expected to increase specificity (fewer false positives). This criteria is more within the range of time that the clinician would perceive a change as being significant or would even be able to detect it.

Second, computer-assisted signal processing may allow certain types of artifact to be averaged into the QRS template.[21-22] Significant baseline drift due to respiration and motion may be incorporated, producing artifactual ST depression. However, this is likely to occur only during the vigorous motion of the torso observed during exercise treadmill testing. Additionally, variation in the method of QRS detection and template alignment of QRS complexes between manufacturers can result in inaccurate J-point determination and erroneous ST-segment measurements. Dysrhythmias, especially ventricular bigeminy, and high-frequency electrocautery can also distort the averaged complex in some computerized systems.

Although validation of this technology as an accurate representation of the raw unprocessed ECG was not a specific aim of our protocol, we were able to verify qualitatively that median complex ST segment changes were present on a real-time 12-lead ECG obtained automatically every 10–15 min during the monitoring period. In 59% of the median complex ECG episodes, a real-time ECG fell within a median complex episode. In all of these real-time ECGs, ST response was qualitatively similar to the median complexes. In the remainder of the median complex episodes (41%), there was no overlap and comparison was not possible. Thus, in this comparison, the use of median complexes were as sensitive as real-time ECGs.

Many factors are known to affect the sensitivity and specificity of the ECG response to ischemia,[23] a number of which are likely to be encountered perioperatively (hypokalemia, hypothermia, respiratory alkalosis, changes in serum glucose, etc.). Controlling for all these factors is difficult given the dynamic nature of the perioperative period. However, an additional factor that the clinician must consider is the patient's baseline ECG morphology. The specificity of the ECG response during exercise stress testing in patients with resting ST-T wave abnormalities is lower than in those with a normal ECG.[8] The effects of left ventricular hypertrophy on sensitivity and specificity are controversial, and have not been well documented. Left anterior fasicular hemiblock, by reducing the normal R/S ratio in V_5, may reduce sensitivity. ST depression in leads V_4–V_6 in the presence of right bundle branch block has been shown to be more specific than changes in V_1–V_3.[24] The ECG in patients with left bundle branch block is considered to be almost completely insensitive.

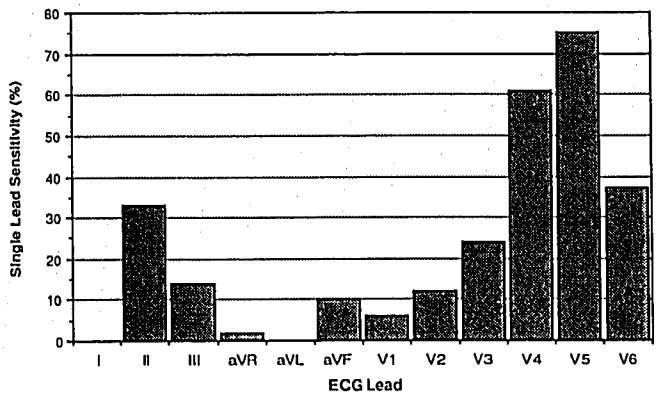

FIG. 3. The distribution of ischemic ST segment-changes in each of the 12 leads considered individually is shown. The number of ST segment-changes in each lead shown in Figure 2 has been summed. The estimated sensitivity was calculated from the number of changes in a single lead as a percentage of the total number of episodes. Sensitivity was highest in lead V_5 (75%).

Restricting our study to those with a normal resting ECG would minimize these concerns, although such an approach would be clinically "artificial," as an abnormal baseline ECG, common in this population, is associated with a high incidence of CAD.[25] Although most authors have excluded patients with left bundle branch block, other inclusion or exclusion criteria have not always been stated explicitly. We included a small number of patients with left ventricular hypertrophy (n = 4), right bundle branch block (n = 1), left anterior fasicular block (n = 2), and one patient taking digoxin. However, the changes detected were similar to those of patients with a normal baseline ECG, with most changes detected in V_5. As our purpose was to describe the maximally sensitive ECG leads without regard for true sensitivity and specificity, we feel that incorporating these patients provided useful information.

DISCUSSION OF RESULTS

This is the first intraoperative study using a continuous recording of the 12-lead ECG to estimate sensitivity of single- and multiple-lead combinations in a patient population with a high prevalence of CAD. Leads II and V_5, the currently recommended combination for perioperative ECG monitoring, detected only 80% of ischemic episodes, while the use of V_4 and V_5 was 90% sensitive. This augmented sensitivity was due primarily to ST depression in V_4 not present in either V_5 or lead

II (16% of episodes), while ST depression in lead V_3 accounted for the remainder (4% of episodes). Based on two episodes in which a marked degree of ST elevation in V_2 (>2mm) occurred in the presence of minimally significant ST depressions in V_5 and lead II, V_2 might be added to the list of optimal leads. Clinicians are likely to perceive significant ST elevation in the anteroseptal leads (V_1–V_3) as more important than minor degrees of ST depression in V_5 or II, especially if baseline ST segment abnormalities are present. In this study, the lateral leads, I and aV_L, were found to be insensitive.

Our results are consistent with those obtained by other investigators studying lead sensitivity during exercise treadmill testing, in which monitoring 12 leads (or more, when using bipolar modifications of V_5) increased sensitivity approximately 15% (range 4–22%) over the use of V_5 alone.[8] In studies in which coronary anatomy was verified, specificity decreased slightly (5–8%) with most false positive responses occurring in the inferior leads.[8] In this study, we assumed that all ischemic changes were true positive responses (100% specificity). Thus, our estimates of sensitivity must remain imprecise, as we did not compare these data to other objective measures of ischemia.

A surprising finding was the very low incidence of ECG ischemia detected by the clinician. In only five of the 25 patients was "clinically significant ischemia" (*i.e.*, ischemia that was noted on the anesthesia record or recovery room/intensive care unit records) detected. The clinicians used either a three-lead (generally monitoring either lead II, modified V_5, or lead III) or five-lead (allowing a choice of six limb leads and a unipolar V_5) monitor with the clinicians and the research V_5 leads placed as close together as possible. These monitors allowed continuous visual display of only one lead, and, generally, V_5 was used. Thus, the clinician could have been expected to detect at least 75% of all episodes. However, there are several explanations for the low rate of detection. First, as the median duration of the episodes was 10 min, one-half were of shorter duration and 31% were <5 min in duration. Thus, the clinician or nursing staff (outside of the operating room) may not have noticed them, as they were not observing the monitor at the time they were present. In the absence of ST segment trending as employed by Kotter *et al.*,[14] there would be no way to detect these brief changes. Second, interpreting subtle changes in ST segment position, especially from an abnormal baseline morphology, often requires close scrutiny and time to compare the change to the baseline before acting on it. In the busy operating room environment, this may not always be possible. In addition, different observers with varying levels of training may attribute different levels of clinical significance to such changes.

The Significance of V_4 and V_5

Our findings that V_4 can contribute significantly to the overall sensitivity of the ECG response in 12 leads is consistent with a recent exercise treadmill study by Miller *et al.*[26] Forty-four patients with both positive exercise treadmill and exercise-thallium tests were studied allowing calculation of sensitivity with reasonable accuracy. V_4 alone was 84% sensitive, V_5 alone 85% sensitive, and the two together, 100% sensitive. Fourteen percent of all patients were positive in V_4 alone, and 16% were positive in V_5 alone. Although we found a lower sensitivity for V_4 and V_5 (61 and 75%, respectively), we found that 90% of all episodes involved either V_4 or V_5.

Other factors could account for the high sensitivity of V_4 in this study, such as inaccurate placement of leads closer to the V_5 position, sex differences, or abnormal body habitus. In this study, most of our patients were elderly and physically inactive males with a high incidence of obesity and chronic obstructive lung disease. Furthermore, operative positioning (Trendelenberg's position and the use of abdominal retractors) can displace the abdominal viscera and diaphragm superiorly with resultant horizontal displacement of the heart and alteration of the normal orientation of QRS-ST vectors. This differs from exercise treadmill testing in which patients are studied either erect during exercise or supine during recovery, with fewer factors causing exaggerated diaphragmatic displacement.

Detection of ST Segment Elevation

During exercise stress testing, ST-segment elevation is uncommon in patients without infarction or variant angina (0.2–1.7%), while it is relatively common in those with variant angina (10–30%).[27] A similar pattern has been noted in studies of ambulatory patients.[28–29] In the patient with unstable angina, ST-segment depression may alternate with elevation in the same lead, indicative of coronary vasomotion ranging from subendocardial to transmural ischemia.[30–31] ST-segment elevation in a non-Q wave lead reflects severe transmural ischemia, identifies akinetic or dyskinetic wall motion, and closely correlates with coronary-artery lesions in the corresponding anatomic region of the heart.[32] These findings contrast with ST depression, which correlates poorly with wall motion abnormalities or the site of coronary artery lesions.[32] Leads V_4–V_6 infrequently display ST elevation,[32] whereas leads V_2 and III are the most sensitive for detecting ST elevation in patients undergoing percutaneous transluminal coronary angioplasty[33] or presenting with acute inferior or anterior myocardial infarction.[34]

In the perioperative settting, most cases of ST elevation have been reported in patients undergoing coronary artery bypass grafting (CABG), and are attributed to coronary artery spasm,[35] although graft occlusion and obstruction have also been implicated as causes.[36] Clinically recognized ST elevation is rare in patients undergoing noncardiac surgery, and has been reported only anecdotally.[37] Our findings confirm its low incidence (12% of episodes), yet show that, in some instances, it can go undetected if the anteroseptal leads are not monitored. Due to the relatively small number of patients who developed ischemia and the low incidence of postoperative infarction, we are unable to correlate the presence of ST elevation with outcome. In this series, two patients developed ST elevation in the anteroseptal leads with associated ST depression in anterolateral or inferior leads, while one patient developed inferior ST elevation associated with ST depression in the anteroseptal leads. Although none of these patients developed postoperative infarction, one had a postoperative course complicated by congestive heart failure and a cerebrovascular accident, and another had three-vessel CAD, ultimately requiring coronary artery bypass. The documented association of proximal lesions of the left anterior descending artery with ST elevation in the anteroseptal leads[19] would suggest that these patients have a considerable amount of jeopardized myocardium, and may, therefore, be at higher risk for postoperative infarction.

Comparison with Previous Intraoperative Studies

How do our results compare with those of other intraoperative studies? Dalton[3] was the first to recommend the routine use of a lateral precordial lead in patients with known or suspected CAD. Although he reported on the safety of his technique (involving a subcutaneous spinal needle and two electrocardiographs) in over 1500 patients, little clinical data were presented. A short time later, Kaplan recommended the use of V_5, illustrating its value in four patients in whom changes were seen in this lead in the absence of changes in the limb leads.[4-5] In these anecdotal reports, other precordial leads were not used, and no attempt was made to quantitate sensitivity. Roy *et al.* were the first to apply multi-lead computer-assisted ECG to the perioperative setting.[9] Compared with our incidence of 24%, they reported a 38% incidence of ischemic ECG changes (11 of 29 patients) in which only two of 11 ischemic episodes were detected on the standard lead II; however, the location and magnitude of change in the specific leads were not discussed. Smith *et al.* monitored a seven-lead ECG (limb leads and V_5) on an intermittent basis in 50 patients undergoing vascular or CABG surgery, and detected 11 ischemic episodes.[11] Only four of these were positive in V_5, while nine were positive in at least one inferior lead and four were positive in a lateral lead. The low sensitivity of V_5 in their study is difficult to explain. Saarnivaara *et al.* continuously monitored V_1–V_6 in 82 general surgical patients undergoing microlaryngoscopy, and reported an 8.5% incidence of "ischemic ST depression."[13] However, no other quantitative data were reported. Kotter *et al.*, using a microcomputer-augmented trended orthogonal lead set (V_5, aV_F, and a V_1 lead placed on the back opposite the normal position), monitored 312 patients undergoing cardiac surgery.[14] Although the value of such a system in detecting and treating ischemia was emphasized, they presented no quantitative data on the nature or localization of the ischemic response. Thus, although several sophisticated studies have investigated and delineated the incidence of ischemia, along with its relation to operative events or hemodynamics, there is still little objective data on which to base selection of the most sensitive monitoring leads.

Summary and Clinical Recommendations

Our results confirm that V_5 is the most sensitive (75%) of the 12 leads for the intraoperative detection of ischemia, followed by V_4 (61%). The standard clinical combination, leads II and V_5, detected 80% of ischemic episodes, while the addition of V_4 to V_5 or II/V_5 enhanced sensitivity to a greater degree (90 and 96%, respectively). Little, if any, information was derived from monitoring lateral limb or other inferior leads. Rarely, marked ST segment elevation may occur in leads V_1–V_3 with only minor ST depression in II or V_5.

How should our results be applied clinically? First and foremost, when applying electrodes to the patient, every attempt should be made to place leads (especially the precordial leads) as close to the standard anatomic positions as possible. In this study, the use of multiple precordial leads was found to be technically feasible in a wide variety of surgical procedures, including those involving high abdominal incisions. With the use of sterile plastic adhesive drapes, skin could be prepared close to the ECG electrodes. No complications attributable to the use of multiple leads, which remained in place for a prolonged period, were evident.

The only group of patients in whom this approach is not feasible are those undergoing thoracotomy, especially on the left side. This is unfortunate, as many of these patients are at risk for CAD, and monitoring precordial leads is not possible. With the elimination of the lateral precordial leads, 67% of ischemic changes would go undetected. As well, the effects of an open chest and

the decubitus position on the ECG may alter normal patterns of ST segment response. The use of a lateral precordial lead an interspace above or below the incision might be helpful in this setting.

Other factors must be taken into consideration when deciding how many leads to monitor. In this report, ECG data were not analyzed in comparison to other objective measures of ischemia. Therefore, these estimates of sensitivity remain imprecise. Also, in the busy operating room environment, the clinician may not have the necessary time to monitor and analyze additional ECG information. Automated ST trending such as that employed by Kotter *et al.* may be helpful,[14] but the results of such an approach must be validated. At the present time, continuous 12-lead ECG monitoring would appear to be practical only for research studies.

This study confirms previous recommendations for the routine use of a V_5 lead (either uni- or bipolar) in all patients at risk for ischemia. V_4 is more sensitive than lead II, and should be considered as a second choice. However, lead II, superior for detection of atrial dysrhythmias, is more easily obtained with conventional monitors. The use of all three would appear to be the optimal arrangement for most clinical needs, and is recommended if the clinician has the capability.

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Appendix

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