Detection of perioperative myocardial ischaemia

N. D. Edwards and C. S. Reilly

Morbidity and mortality from cardiac complications in patients undergoing surgery continues to be of major concern. In the U.K., 12-20% of patients undergoing surgery have preoperative evidence of myocardial disease [27, 106]. In 1977, Goldman and colleagues formulated the "cardiac risk index", implicating previous myocardial infarction (MI), heart failure and unstable angina as major determinants of postoperative cardiac events [39]. In 1979, Roy, Edelist and Gilbert showed that there is a high incidence of perioperative myocardial ischaemia in patients with coronary artery disease (CAD) [98]. More recent studies have confirmed these findings, and shown the presence of myocardial ischaemia before, during or in the early period after operation to be predictors of postoperative cardiac morbidity. However, there remains some controversy as to which are the most useful methods of detection and when they are best applied (tables I, II).

It has been shown that improved perioperative monitoring and treatment can reduce the rate of myocardial reinfarction [92, 104], and that treatment aimed at reducing perioperative ischaemia may reduce postoperative cardiac morbidity [108, 109]. It is therefore of great importance that perioperative ischaemia is detected and treated promptly in order to reduce postoperative cardiac complications.

Invasive monitoring studies have shown that the earliest manifestations of myocardial ischaemia are abnormalities in relaxation during diastole, followed by abnormalities of contraction during systole [55, 129]. Such wall motion abnormalities may be detected non-invasively by echocardiography or radionuclear imaging. These changes lead to an increase in left ventricular end-diastolic pressure (LVEDP), followed by ECG ST-segment changes and, finally, symptoms of angina. It is clear that the development of ECG changes and anginal symptoms is a relatively late finding in the development of myocardial ischaemia.

PREOPERATIVE DETECTION OF MYOCARDIAL ISCHAEMIA

The presence or absence of myocardial ischaemia before operation, at rest, during daily activity or on stress testing, may be helpful in assessing cardiac risk and may be used to identify those patients in need of further preoperative assessment or improved preoperative medical treatment. The initial history and examination should reveal those patients who are either known to have CAD (previous MI or angina), or who possess risk factors for the presence of CAD such as hypertension, diabetes or peripheral vascular disease.

ECG

12-lead ECG. Preoperative ECG abnormalities are common in patients with CAD [14, 17, 39], and up to 40% of these changes may have occurred in the previous 2 years [87]. The value of the preoperative ECG as a predictor of postoperative outcome is uncertain, particularly as a wide range of ECG abnormalities may be associated with ischaemia (table III). The specificity of these changes varies, and the majority are not diagnostic of ischaemia when found in isolation. Goldman and colleagues [39] found that preoperative ischaemic changes in the ECG were not predictors of postoperative outcome, although the presence of preoperative arrhythmias was. Other studies have shown similar findings [60, 72], but some have shown an association between an abnormal ECG before operation and adverse outcome [14, 18, 103, 124]. The standard 12-lead ECG only rarely detects transient ischaemic changes as the recording only covers a 10-20 s period.

Exercise ECG. A normal resting ECG does not exclude the possibility of severe CAD. Indeed, Tomatis, Fierens and Verbrugge [115] showed that 30% of patients with a normal resting ECG, undergoing peripheral arterial surgery, had a 75-100% obstruction of a major coronary vessel. The exercise ECG has been shown to be a good predictor of the physiological significance of coronary stenosis in patients with a normal resting ECG and no left ventricular hypertrophy or previous MI [128]. Preoperative exercise testing might be expected to be of greater value than standard ECG recording, and this has been assessed in several studies (table I). Cutler and colleagues studied 100 patients scheduled to undergo peripheral vascular surgery [22], and found that, of 73 patients who had a normal resting preoperative ECG, 14 developed an ischaemic ECG on exercise. Of the 48 patients who subsequently underwent surgery, six developed postoperative MI,
TABLE I. Studies assessing the predictive value of perioperative ECG analysis

<table>
<thead>
<tr>
<th>Perioperative period</th>
<th>Method of detection</th>
<th>Source</th>
<th>Year</th>
<th>Type of surgery</th>
<th>No. of patients</th>
<th>Predictive morbidity</th>
</tr>
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<tbody>
<tr>
<td>Preoperative</td>
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<td></td>
<td></td>
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<tr>
<td></td>
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<td>566</td>
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<tr>
<td></td>
<td>Von Knorrung [124]</td>
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<td>214</td>
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<tr>
<td></td>
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<td></td>
<td>Shah [103]</td>
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<td></td>
<td>Baby [89]</td>
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<td>Fleisher [34]</td>
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<tr>
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<td>Regular ECG tracings</td>
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<td></td>
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<tr>
<td></td>
<td>Slogoff [108]</td>
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<tr>
<td></td>
<td>Slogoff [109]</td>
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<td></td>
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<td></td>
<td>Mangano [73]</td>
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<td></td>
<td>Mangano [73]</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Smith [112]</td>
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<td>Cardiac</td>
<td>50</td>
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</table>

TABLE II. Studies assessing the predictive value of detecting perioperative ischaemia by methods other than the ECG

<table>
<thead>
<tr>
<th>Perioperative period</th>
<th>Method of detection</th>
<th>Source</th>
<th>Year</th>
<th>Type of surgery</th>
<th>No. of patients</th>
<th>Predictive morbidity</th>
</tr>
</thead>
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<tr>
<td>Preoperative</td>
<td>Dipyridamole thallium imaging (DTI)</td>
<td>Boucher [9]</td>
<td>1985</td>
<td>Vascular</td>
<td>54</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cutler [22]</td>
<td>1987</td>
<td>Aortic</td>
<td>116</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lette [59]</td>
<td>1989</td>
<td>Non-cardiac</td>
<td>66</td>
<td>Yes</td>
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<tr>
<td></td>
<td>Combined clinical data and DTI</td>
<td>Eagle [29]</td>
<td>1987</td>
<td>Vascular</td>
<td>111</td>
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<tr>
<td></td>
<td></td>
<td>Eagle [28]</td>
<td>1989</td>
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<td>254</td>
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<tr>
<td></td>
<td>Dobutamine echocardiography</td>
<td>Laika [56]</td>
<td>1992</td>
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<td>60</td>
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<td>Peroperative</td>
<td>Transoesophageal echocardiography</td>
<td>Smith [111]</td>
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<td></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td>Watters [126]</td>
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TABLE III. ECG abnormalities associated with myocardial ischaemia

<table>
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<th>Conduction abnormalities</th>
<th>Arrhythmias</th>
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<tbody>
<tr>
<td></td>
<td>Q-waves</td>
</tr>
<tr>
<td></td>
<td>Poor R-wave progression</td>
</tr>
<tr>
<td>ST segment</td>
<td>&gt; 1 mm depression</td>
</tr>
<tr>
<td>T-wave</td>
<td>&gt; 2 mm elevation</td>
</tr>
<tr>
<td></td>
<td>Isoelectric</td>
</tr>
<tr>
<td></td>
<td>Inverted</td>
</tr>
<tr>
<td></td>
<td>Reverted</td>
</tr>
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</table>

all of whom had exercise ECG ischaemia. Arous, Baum and Cutler [1] studied 808 patients undergoing major peripheral vascular surgery. Of the 135 patients who had a positive preoperative exercise test, 56 underwent surgery regardless of test results, 18 suffering postoperative MI. Twenty-one of these 56 patients had no history of CAD and a normal resting ECG, but five nevertheless suffered postoperative MI. In contrast, Carliner and colleagues [14] assessed the value of routine preoperative exercise ECG testing in 200 patients older than 40 yr
undergoing elective major non-cardiac surgery, but did not find it to be a predictor of postoperative outcome. It would seem from these studies that the exercise ECG is of limited value as a routine screening procedure for identifying at-risk patients, but that it may be of value for subgroups at greater risk of CAD, such as patients undergoing vascular surgery.

The effects of exercise on the ECG may not, however, provide an accurate reflection of the effects of anaesthesia. During exercise testing, patients are upright and there is a large increase in their oxygen consumption, with an increased heart rate and cardiac output and a decrease in systemic vascular resistance. This is not a good model for anaesthesia, during which the patients are lying flat and the changes in heart rate are only moderate. In addition, some patients may be limited in their ability to undergo stress testing, particularly those patients with symptomatic peripheral vascular disease.

Ambulatory ECG monitoring. Continuous ambulatory ECG monitoring may be a superior alternative. Originally designed for the detection of arrhythmias, ambulatory electrocardiography has been developed to allow accurate detection and measurement of changes in the ST-segment.

There are two types of system available for continuous ambulatory ECG examination: the conventional Holter tape recorder and playback system and the solid-state, real-time analysis microcomputer and report generator. The validity of the earlier Holter monitors in accurately reproducing ST-segment changes was questioned, because of the limited low frequency response of both the recording and playback systems. However, later models were shown to have satisfactory ST-T segment reproducibility, and the ability of these systems to detect ST-segment changes reliably is now accepted [50].

The solid-state, real-time analysis microcomputer examines a digitized ECG signal without the distortions introduced by tape recording and playback methods. Its validity in recording ST-T segment abnormalities has been confirmed, although possible drawbacks of the system are the need for a stable baseline, and that failure to identify ventricular arrhythmias may contribute to false positive results [50].

Ambulatory ECG monitoring detects the frequency and duration of silent myocardial ischaemia throughout a 24–48 h period, although they are not as yet able to assess the extent or severity of myocardial ischaemia. In order to reduce the incidence of false positive results, significant ischaemia is defined arbitrarily as transient ST-segment depression greater than 1 mm from baseline at 0.08 s after the J point lasting for at least 1 min. Although false positive results may occur in the apparently healthy [86], ST-segment changes in patients at risk of CAD correlate well with measurements of myocardial perfusion using positron tomography [128]. Tzivoni and colleagues have demonstrated a marked day-to-day variability in the number and duration of ischaemic episodes [119], but suggested one 24-h ambulatory ECG to be adequate for clinical examinations. Nabel and colleagues [80], however, have argued that at least 48 h is required to assess accurately ischaemic activity in a single patient.

Ambulatory ECG monitoring has shown that myocardial ischaemia often occurs in patients with CAD during normal daily activity. It is typically silent [24], often unrelated to heart rate [13, 24], and may be as important an indicator for the development of subsequent MI, as symptomatic ischaemia [40]. Preoperative ambulatory ECG monitoring has revealed that up to 80% of patients with or at risk of CAD, undergoing non-cardiac surgery, have silent ischaemic episodes before operation [67, 70, 79, 83, 89]. Preoperative ambulatory ECG monitoring may therefore be of value in the assessment of cardiac risk. Raby and colleagues [89] studied 176 patients undergoing elective vascular surgery. Thirty-two (18%) had episodes of preoperative ischaemia, and 12 of those had postoperative cardiac events, compared with only one of the 144 patients who did not have ischaemia before operation. Pasternack and colleagues [83] studied 200 patients undergoing vascular surgery, 78 (39%) of whom had silent preoperative ischaemia. Nine patients, all of whom had episodes of silent preoperative ischaemia, had postoperative MI. Fleisher and colleagues [34] investigated the predictive value of preoperative silent ischaemia in 146 patients having vascular and non-vascular surgery. Only 24 patients (16%) had preoperative ischaemia, and nine of those had postoperative cardiac events, as did eight of the 122 patients without preoperative ischaemia. However, in that study the patients were monitored for a shorter time before operation than in the studies by Raby's and Pasternack's groups, which may explain the poorer predictive value. In contrast, Mangano and colleagues were unable to show an association between myocardial ischaemia detected by preoperative ambulatory ECG, and postoperative outcome [72].

An interesting method of detecting the haemodynamic significance of ST-segment changes seen during exercise testing or ambulatory monitoring is by using concomitant pulmonary artery pressure monitoring [64], although its value in preoperative assessment is not known.

Further studies are clearly required to clarify the value of preoperative ambulatory ECG monitoring in the prediction of perioperative outcome. It may also prove to be of value in the prediction of long-term prognosis [88].

Unfortunately, the value of exercise ECG and of ambulatory ECG monitoring in detecting myocardial ischaemia is greatly reduced in the presence of other variables which affect the ST-segment, such as conduction abnormalities, pacing, ventricular hypertrophy and electrolyte imbalance, and in the presence of drugs such as digoxin [50]. Patients in whom such factors are present may need to be assessed by other methods.

Radionuclide imaging

Perfusion scintigraphy is used to detect MI, quantify myocardial perfusion abnormalities and calculate ventricular performance and wall motion indices. Technetium pyrophosphate (hot spot
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imaging) and thallium 201 (cold spot imaging) are the radionuclides used commonly. Hot spot imaging involves the uptake of the isotope into acutely infarcted tissue and detects MI reliably, but is unsuitable for detecting reversible myocardial ischaemia. Cold spot imaging, in contrast, involves isotope which is taken up into normal myocardium. A decreased blood supply to an area of myocardium reduces uptake of the isotope in that area, resulting in a "perfusion defect".

Thallium 201 imaging is highly sensitive for detecting MI and myocardial ischaemia, but less specific. Fixed perfusion defects indicate infarction, and transient (or reversible) defects indicate myocardial ischaemia. The sensitivity of thallium scanning is improved if performed under conditions of high coronary blood flow such as occurs during exercise, or with the administration of coronary vasodilators such as dipyridamole [12]. Dipyridamole produces marked coronary arterial vasodilation, with less effect on peripheral arterioles. In myocardium perfused by normal arteries, administration of dipyridamole results in a substantial increase in blood flow to both endocardial and epicardial layers [32]. However, an increase in flow across stenosed arteries results in a decrease in pressure distal to the stenosis, and subsequent transmural "coronary steal" from the subendocardium to the subepicardium, leading to subendocardial ischaemia [4, 5]. Myocardial extraction of thallium is great because the heart recognizes it as potassium. In normally perfused myocardium, i.v. administered dipyridamole is associated with an increased uptake and more rapid clearance of thallium-201. The presence of a coronary stenosis results in diminished uptake and delayed clearance [4, 5], producing an initial thallium-201 defect, with subsequent delayed redistribution.

Dipyridamole thallium imaging (DTI) has been shown to be of value in assessing risk after MI [11, 58] and there has recently been a large amount of interest in the detection of ischaemia by DTI as a predictor of postoperative outcome (table 11). DTI involves an initial i.v. injection of dipyridamole over 4 min, followed, approximately 3 min later, by thallium-201 injected i.v. Initial imaging is then performed. Delayed images are obtained 2.5–4.0 h later, to evaluate the presence or absence of redistribution [3]. A "fixed defect" showing no thallium redistribution indicates the presence of scar tissue, whereas a "reperfusion defect", which demonstrates redistribution, indicates an ischaemic but viable area of myocardium. Late redistribution imaging at 18 or 24 h, or reinjection of a second dose of thallium-201, may enhance the ability to differentiate between fixed defects and reperfusion defects [96]. Thallium imaging is also possible using orally administered dipyridamole, although there is variability in dipyridamole absorption between patients, and less predictable serum concentrations.

Boucher and colleagues [9] were the first to describe the use of DTI to stratify cardiac risk following surgery. They studied 54 patients with suspected CAD undergoing peripheral vascular surgery. Patients with unstable angina, MI in the previous 3 months, cardiac failure or multiple ventricular arrhythmias were excluded, as they were already considered to be at high risk. Six patients proceeded to coronary angiography. Of the remaining 48 patients, 16 had redistribution abnormalities on DTI, of whom eight developed postoperative cardiac events. None of the patients without a redistribution abnormality suffered a postoperative event. Of the six patients who had angiography, one patient was considered not to require angioplasty and underwent vascular surgery uneventfully. Four patients underwent coronary artery bypass grafting, and follow-up scans revealed no redistribution abnormality. All four patients then underwent vascular surgery and none suffered a postoperative cardiac event.

Several other studies have confirmed the value of DTI in cardiac risk stratification [21, 57, 59, 61, 94, 113, 130]. Leppo and colleagues [57] found that, whilst exercise-induced ST-segment changes were not related to postoperative outcome, in patients who demonstrated thallium redistribution the risk of a postoperative cardiac event was 23 times greater than in patients without redistribution. Cutler and Leppo [21] also reported that, in patients undergoing abdominal aortic surgery, those whose DTI scans showed thallium redistribution had a 12 times increased risk of postoperative cardiac events. Although these studies show the absence of a "reperfusion" defect on DTI to have a high negative predictive value, others have reported significant morbidity in patients with normal scans or "fixed" perfusion defects [33, 69]. Indeed, Mangano and colleagues have expressed doubt as to the value of preoperative dipyridamole thallium testing [74]. However, the method of patient selection in their study led to a low incidence of postoperative myocardial events, and their conclusions have been criticized [85].

Although studies show DTI alone to have high sensitivity for risk stratification, it has poor specificity. This can be improved when DTI is combined with clinical data. Eagle and colleagues [29] assessed patients as to the presence of five clinical markers (previous MI, congestive heart failure, angina, diabetes, or Q-waves on ECG). The absence of all of these markers indicated a very low risk of postoperative cardiac morbidity, even in the presence of redistribution on DTI. DTI was most helpful in stratifying patients with one or more of these clinical markers before operation, 45% of such patients with thallium redistribution having postoperative ischaemic events, compared with 7% of those without. In a further study, Eagle and colleagues suggested that DTI was of greatest value in patients at "intermediate" risk, who had only one or two of these clinical variables [28]. The specificity of DTI may also be improved by quantifying the severity and extent of myocardial reperfusion defects [59, 61, 63]. In addition to perioperative cardiac risk, preoperative DTI has also been shown to be of value in the prediction of longer term prognosis [130].

Evaluation of a technique for detecting ischaemia must also include an assessment of its potential risks. The safety of DTI has been reported by Ranhosky...
and Kempthorne-Rawson [91]. Of 3911 patients, 10 patients had major adverse events, four patients (0.1%) suffered MI (two died) and six (0.15%) developed acute bronchospasm. Minor complications are more common, however, and chest pain, although not a reliable marker of ischaemia, may occur in 20% of patients. The use of adenosine in the place of dipyridamole for thallium imaging is currently under investigation [19]. A study comparing the value of preoperative DTI with preoperative ambulatory ECG monitoring for cardiac risk stratification would be of interest, as the latter technique has no reported side effects.

Echocardiography

Two dimensional (2-D) echocardiography is of great value in the assessment of ventricular function. It provides reliable estimates of ventricular filling and ejection, wall thickness and mass, from which can be calculated end-diastolic volume, ejection fraction, systolic wall stress and contractility. Myocardial ischaemia is associated with abnormalities in ventricular wall motion and wall thickening. 2-D echocardiography may be used to detect these segmental wall motion abnormalities (SWMA) and diagnose the presence of acute myocardial infarction [45]. Exercise echocardiography has been shown to have a sensitivity superior to that of exercise electrocardiography in the detection of single vessel coronary disease [99]. However, artefact caused by the movement of exercise and increased ventilatory effort makes the technique technically difficult. Stress echocardiography using pharmacological agents such as dipyridamole, dobutamine or adenosine may be a suitable alternative [76].

While the value of preoperative exercise echocardiography is unknown, Tischler and colleagues [114] have reported impressive results using dipyridamole echocardiography as a method for cardiac risk stratification. They studied 109 unselected patients undergoing elective vascular surgery. Of the nine who had positive tests, seven had postoperative cardiac events, compared with one of the 100 patients who had a normal scan. The value of dobutamine stress echocardiography has been investigated by Lalka and colleagues in 60 patients undergoing elective aortic surgery [56]. Of 38 patients with an abnormal scan, 11 suffered a postoperative cardiac event, compared with one of 22 patients with a normal scan. Further studies in this area will be of great interest.

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ECG

The ECG is used as a routine monitor during anaesthesia. The detection of heart rate and arrhythmias is accurate, but ST-segment analysis on standard monitors has poor sensitivity and specificity. This is the result of several factors including monitoring design, limited lead selection and failure in observation by clinicians. Recommendations for ECG recording require a flat frequency response at a bandwidth of 0.05–100 Hz [84]. In the noisier clinical setting of the opening theatre, monitors usually have a narrower bandwidth, filtering out extraneous signals which may interfere with diagnosis. Reduction in the high frequency response decreases distortion from muscle movement and electrical equipment, and increasing the lower frequency response reduces baseline drift caused by ventilation and poor electrode contact. Unfortunately, reducing the low frequency response may lead to erroneous ST-segment depression [8]. However, despite observing variability between systems with different low frequency responses, Slogoff and colleagues concluded that, when monitored in patients at high risk of CAD, ST-segment changes are highly specific and not artefactual, and that an ECG system that makes ST changes more rather than less detectable is appropriate for patients with known CAD in the perioperative setting [110]. However, they also warned of the dangers of interpreting ST-segment depression on monitors with reduced low frequency response in populations not known to have CAD.

The detection of disturbances of cardiac rhythm and conduction is considered to be best using standard lead II, as its axis parallels the electrical axis of the heart and usually gives the clearest demonstration of the P-wave [118]. The best leads for the detection of ST-T wave changes depend upon the area affected. Leads V4 and V5 are useful for monitoring anterior ischaemia and leads II, III and AVF view the heart inferiorly. Right ventricular dysfunction is probably best viewed by a V4R lead (4th intercostal space, right midclavicular line) [51, 118]; its value in detecting intraoperative ischaemia in patients with right-sided coronary occlusive disease has been demonstrated [23]. Posterior ischaemia is monitored best with an oesophageal lead. About 90% of ST-segment information obtained during the exercise ECG is found in lead V5, and this lead was suggested, therefore, as the most appropriate for detecting intraoperative ischaemia [47]. Monitoring of lead V5 requires a five-lead system. As most ECG monitors provide only a three-lead system, most monitores provida the facility of observing only one lead at a time, different bipolar lead configurations have been assessed as to their ability to detect ischaemia, whilst also allowing easier recognition of P-waves [2,35,41]. Of these, lead CM5 (positive lead, precordial V5; negative lead, right sternal border), CS5 (positive lead, precordial V5; negative lead, midpoint of the right clavicle), and CB5 (positive lead, precordial V5; negative lead, middle of the right clavicle or back) would appear to be satisfactory alternatives to a true lead V5 for the detection of intraoperative ischaemia [35,41].

Using continuous 12-lead ECG monitoring during operation, London and colleagues assessed the value of different lead locations in detecting intraoperative ischaemia [65]. Sensitivity was greatest in leads V5 (75%) and V4 (61%). Combining V5 and V4 increased sensitivity to 90%, and the addition of lead II increased sensitivity to 96%. The further addition of leads V2 and V3 increased sensitivity to 100%. The value of multiple-lead analysis of the ECG
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during operation in at-risk patients is thus empha-
sized.

Another important finding of the study by London's group [65] was the poor rate of observation of intraoperative ischaemia by clinicians using stan-
dard ECG monitoring. The authors suggested that the comparatively short duration of ischaemia, the difficulty of applying close scrutiny to the ECG in the busy operating theatre environment and the differences between clinicians in attributing clinical significance to observed changes were all causative factors. This low observation rate can be improved using monitoring capable of continuous computer analysis and display of ST-segment trends, as described first by Kotry and colleagues [54]. Better identification of the beginning and end of each QRS complex permits precise and reliable measurements of the ST segments. A limitation of the early ST-segment monitors was that the isoelectric point and the point in the ST-segment at which ischaemic changes were measured were fixed at 40 ms before the QRS onset and 80 ms after the QRS offset, and this could lead to erroneous results during tachy-
arrhythmias [31]. Improved monitors are now available which allow the clinician to alter with a cursor the points at which these measurements are made, and incremental averaging also increases the accuracy of ST-segment processing [127]. Such systems greatly improve intraoperative detection of myocardial isch-
aemia compared with conventional systems, and have been improved further to allow continuous 12-lead ST-segment analysis [36]. However, ST-seg-
ment analysis may still be misleading, as it has a positive predictive value of only about 35%, and ST-segment monitors are probably best regarded as alarms that cause the clinician to increase vigilance [31]. A potential value of the ECG detection of myocardial ischaemia during operation is as a predictor of postoperative risk. Studies suggest that intraoperative ECG monitoring may be useful in predicting outcome in patients undergoing cardiac surgery [108, 120], but there is less evidence of its value as an indicator of risk in patients undergoing non-cardiac surgery [72, 68].

Pulmonary artery pressure monitoring

In 1981, Kaplan and Wells suggested that changes in the pulmonary capillary wedge pressure (PCWP) trace represented a sensitive and independent indi-
cator of intraoperative myocardial ischaemia [48]. Further apparent evidence suggesting that pulmon-
ary artery pressure (PAP) monitoring may be of value in detecting myocardial ischaemia in patients with CAD came from Rao, Jacobs and El-Etr [92], who studied patients with previous MI undergoing non-cardiac surgery. They found that patients with PCWP greater than 25 mm Hg had a 28% incidence of reinfarction, compared with a 1% incidence in patients whose PCWP was less than 25 mm Hg. In addition, a more recent study by Berlauk and colleagues found that the use of PAP monitoring to optimize cardiovascular haemodynamics before op-
eration improved outcome [7]. However, in two other recent studies of patients undergoing cardiac and non-cardiac surgery [46, 116], information from pulmonary artery catheterization did not play a major role in influencing outcome.

Myocardial ischaemia leads to an increase in PCWP, and the appearance of new a-c or v waves. These changes can also occur with acute increases in afterload as a result of catecholamine release, a decrease in pulmonary venous compliance or mitral regurgitation. In patients with MI, PCWP has been shown to be a poor reflection of left ventricular end-
diastolic pressure (LVEDP), which during ischaemia may exceed PCWP by 10-15 mm Hg [90]. Fur-
thermore, PCWP cannot be used for continuous monitoring, as the catheter must be wedged. Several studies have shown that PCWP is not reliable in detecting intraoperative myocardial ischaemia [43, 122]. Thus the value of PAP monitoring in detecting intraoperative myocardial ischaemia has not been proven, and the use of continuous monitors of SWMA that would allow earlier intervention and treatment of myocardial ischaemia may be of more value.

Radionuclear imaging

Diprydamole thallium scanning may be used to detect myocardial ischaemia in the anaesthetized patient. In an interesting study, DTI performed immediately after intubation detected perfusion defects which were not present before operation in 10 of 22 patients undergoing CABG surgery [52]. None of these patients showed any ST-segment changes in the V5 ECG lead, or any PCWP changes. In two of the patients, these changes were still present on a postoperative scan, one patient having cardiac enzyme evidence of postoperative MI.

Cardiokymography

The cardiokymograph is an electronic device used as a non-invasive method of detecting abnormalities of regional wall motion, producing an analogue representation [6]. The probe is placed on the chest wall, and consists of a capacitative plate as part of a high-frequency, low-power oscillator which emits a low energy magnetic field. Motion within this field causes a change in effective capacitance, producing a change in frequency of the oscillator. A signal-
processing unit converts the frequency of oscillation into an output voltage signal. Cardiokymography (CKM) has been shown to be a better indicator of CAD than the ECG [6], and exercise CKM to be of value similar to exercise thallium imaging, and superior to exercise ECG [107]. Hagglmark and colleagues, in a study of 53 patients [43], found that CKM detected 83% of intraoperative myocardial ischaemic episodes, com-
pared with a V5 lead ECG detection rate of 44%. However, CKM is limited by its inability to detect wall motion that is not anterior, the presence of interference produced by other artefactual motion and the practicalities of maintaining the probe position on the chest.

Transoesophageal echocardiography

The intraoperative detection of myocardial ischaemia using 2-D echocardiography was not prac-
ticable, until a transducer which could be positioned in the oesophagus was introduced [101]. Echocardiography uses frequencies in the range 1–7 MHz. Frequencies at the high end of this range give high resolution but have low penetration whereas, at lower frequencies, penetration is improved at the expense of decreased resolution. As there is no need to penetrate the chest wall, transoesophageal echocardiography (TOE) utilizes frequencies between 3.5 and 7 MHz, affording excellent resolution [71]. TOE can be placed in an awake patient under local anaesthesia, but in surgical patients is usually placed after induction of anaesthesia and intubation of the trachea. The transducer is inserted through the mouth and advanced 35–40 cm, initially to obtain a view of the aortic valve. Further advancement then allows all four heart chambers to be viewed. Finally, by angling the transducer forward and advancing it a further 2–5 cm, a cross-sectional image of the left ventricle, including a short-axis view at the level of the papillary muscle, is obtained [12]. This is the view most commonly used in assessing SWMA, which can be detected readily in the anterior, septal, posterior and lateral walls. If the heart is not enlarged, a cross-sectional view of both ventricles can be obtained frequently. However, SWMA in the apical and basal areas may be missed. The recent introduction of the biplanar TOE probe, capable of scanning the left ventricle in both short axis and longitudinal views without changing transducer position may have solved this problem [105]. TOE may also be used during operation to assess ventricular volumes and ejection fraction, and to detect air embolus [12]. The incidence of complications with the technique is very low, although it is not recommended in patients with a history of oesophageal disease [121]. Temporary unilateral vocal cord paralysis has been reported after the use of TOE during craniotomy with the patient in the sitting position with the head flexed forwards [20].

In assessing the value of TOE during operation, Smith and colleagues [111] studied 50 patients at high risk of intraoperative myocardial ischaemia who were undergoing major vascular surgery. At predetermined intervals throughout surgery, echocardiograms and multilead ECG were recorded, which were analysed later. SWMA developed during operation in 24 patients. These were transient in 16 patients, but persisted until after skin closure in eight. Six patients developed ECG changes during operation, three of whom had developed SWMA earlier. Three patients had intraoperative MI diagnosed by an increase in serum cardiac enzyme concentrations 8 h after operation; all three had persistent intraoperative SWMA, but only one had intraoperative ECG changes.

Leung and colleagues compared the value of TOE with ambulatory ECG monitoring in 50 patients undergoing coronary artery surgery [62]. After bypass, 18 patients developed SWMA which were not associated with haemodynamic changes and six patients had major postoperative cardiac events. No patient who did not develop SWMA after bypass had a postoperative cardiac event. The authors commented that TOE may be of special value in the post-bypass period, as conduction abnormalities and the use of pacing, which make the ECG difficult to interpret, are common during this time. However, the results of other studies in patients undergoing non-cardiac surgery are not so favourable [66, 126].

In a study by Watters and colleagues of 26 patients with CAD [126], six patients suffered postoperative cardiac events, only three of whom had intraoperative SWMA detected by TOE. London and colleagues [66] investigating 156 patients, observed a poor correlation between SWMA detected by TOE and postoperative cardiac complications. They also noted a poor relationship between intraoperative ECG changes and SWMA. Indeed, in a recent study the same group of researchers showed the detection of myocardial ischaemia with TOE to be of little additional value to 2-lead Holter ECG recording in predicting postoperative cardiac risk [30].

Whilst of obvious potential as a method for detecting intraoperative ischaemia, TOE currently has several limitations [123]:

1. TOE monitoring does not usually begin until the probe has been positioned, after induction of anaesthesia, during which many undetected ischaemic episodes may occur.
2. Probe position and orientation must be attended to very carefully throughout surgery. For accurate detection of wall motion abnormalities, high quality scans of both ventricles are required and this is not always possible.
3. The criteria describing the significance of SWMA in terms of duration and type (hypokinesis, akinesis or dyskinesis) need validation.
4. TOE relies heavily upon the skill of the operator, and on-line detection of ischaemia is as yet unreliable [100].
5. It is expensive.

Validation of the technique of TOE in detecting intraoperative ischaemia is still required.

**Metabolic indicators**

Coronary sinus concentrations of biochemical markers such as lactate [43, 81] or catecholamines [49] may be useful indicators of myocardial ischaemia. However, such methods, whilst useful research tools, are of limited clinical use.

**POSTOPERATIVE DETECTION OF MYOCARDIAL ISCHAEMIA**

The diagnosis of postoperative MI usually relies upon serial 12-lead ECG and measurement of cardiосpecific enzyme concentrations. However, postoperative ECG abnormalities are not uncommon. For example, T-wave changes have been shown to occur within the first 1 h after operation in 20% of patients, and are equally common in patients with and without CAD [10]. T-wave changes cannot therefore be used to diagnose postoperative MI, although they may be indicative of patients at increased risk. Thus the ECG diagnosis of postoperative MI requires the appearance of Q-waves, or persistent ST-T wave changes. In addition, the sensitivity of the 12-lead ECG in determining postoperative MI is limited in the presence of
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conduction abnormalities and pacemakers [117], although attempts have been made to define criteria for the diagnosis of MI in the presence of left bundle branch block [44].

Lactate dehydrogenase (LDH) and creatinine phosphokinase (CPK) are the plasma enzymes most often used to diagnose MI, but they are of limited use after operation. LDH concentrations are affected by biliary surgery and red cell haemolysis, and CPK concentrations increase as a result of muscle trauma during surgery. The creatinine phosphokinase iso-enzyme (CK-MB) is of much greater value. After non-cardiac surgery, if the CK-MB fraction exceeds 5% of the total CPK value, myocardial infarction is probable [38, 95]. After cardiac surgery, the appearance of CK-MB as a result of surgical trauma and revascularization is not uncommon. However, should CK-MB concentrations remain increased beyond 18 h, myocardial infarction is likely to have occurred [25].

A study by Charlson and colleagues [15] showed that almost 50% of patients who had postoperative MI (defined as persistent ECG changes and CK-MB fraction 5% or greater) were asymptomatic, and that the greatest risk for infarction after surgery occurs on the day of operation and the first day after operation. The use of CK-MB analysis was shown to add little to a strategy of recording a 12-lead ECG after operation on the day of operation and on the first two days after operation.

Other techniques available for the detection of postoperative MI, which may help corroboration, include serial technetium 99m-labelled pyrophosphate imaging [77].

The presence after operation of surgical pain, fluid balance abnormalities, anaesthetic drugs and anaesthesias, has the effect that episodes of postoperative myocardial ischaemia are masked and are very difficult to detect clinically. A postoperative 12-lead ECG, for example, will not detect an episode of reversible myocardial ischaemia unless it is occurring at that particular moment of monitoring. The use of continuous ambulatory ECG for the detection of postoperative ischaemia was described first by Griffin, Phipps and Evans [42]. Since then, studies on the prevalence of myocardial ischaemia in the postoperative period have continued to rely upon the detection of ST-segment abnormalities by ambulatory ECG monitoring [93, 97]. It is important that the predictive value of perioperative ST-segment abnormalities is established, as this may be the only way to ascertain their ischaemic “validity” [72].

Studies using ambulatory ECG have shown that the incidence of myocardial ischaemia in patients with CAD, undergoing either cardiac or non-cardiac surgery, increase after operation from that found in the preoperative and perioperative periods [53, 70, 72, 73, 82, 102, 112]. Mangano and colleagues found a two-fold increase in the incidence of ischaemia after operation compared with the periods before and during operation [72]. Myocardial ischaemia is commonest over the first 3 days after operation [78]. It is largely silent, and often unrelated to haemodynamic change, making it difficult to detect clinically.

Several of these studies indicate that postoperative myocardial ischaemia is a more important indicator of adverse cardiac outcome than either preoperative or intraoperative ischaemia [72, 73, 82, 102]. Indeed, Mangano and colleagues [72] showed a nine-fold increase in the risk of a postoperative cardiac event in patients who had ambulatory ECG evidence of postoperative myocardial ischaemia. In addition, it has been shown that the incidence of postoperative myocardial ischaemia after cardiac surgery can be reduced by intensive postoperative analgesia [75], possibly as a result of preventing pain-related tachycardia. Studies assessing the importance of postoperative analgesia in reducing myocardial ischaemia after non-cardiac surgery would be of great interest.

It is likely, therefore, that postoperative myocardial complications may be reduced by early detection and treatment of myocardial ischaemia. Unfortunately, most ambulatory ECG monitoring devices provide information only when the recorder is analysed, after the event. However, the use in the early postoperative period of on-line, computerized ST-segment monitoring which can be programmed to alert staff to the presence of significant deviations in ST-segment and provide immediate print-outs of such episodes, allows ischaemic changes to be promptly recognized and treated [16, 26]. An increase in the number of leads monitored improves the detection of postoperative myocardial ischaemia [102].

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