Review Article

Anaesthesia for abdominal aortic surgery - a review (Part I)

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Key words

ANAESTHESIA: cardiovascular; SURGERY: abdominal aortic; MONITORING: stroke volume, afterload.

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The principles of surgical technique and anaesthetic management have progressed dramatically since Dubost first reported a successful abdominal aortic aneurysm resection in 1952.¹ At that time the detection of an asymptomatic infrarenal abdominal aortic aneurysm was associated with a 50 per cent mortality rate within the first year of diagnosis, 81 per cent within five years and 100 per cent within eight years.²⁻³ Operative mortality rates of 9–18 per cent for elective aneurysm resection were reported in the 1960s.⁴⁻⁷ The 4–9 per cent operative mortality quoted in the early 1970s represented a substantial improvement in outcome.⁸⁻¹⁰ In the past decade a further decline in the 30-day operative mortality to one to six per cent has become apparent (Table I).¹¹⁻¹⁵ Factors contributing to reduced operative mortality include improved surgical techniques, earlier surgical intervention, better patient selection and preoperative management, improved imaging techniques, a greater understanding of the underlying vascular pathophysiology, advances in haemodynamic monitoring, improved anaesthetic agents and techniques, and intensive postoperative care.

Rapid exsanguination following rupture of an abdominal aortic aneurysm is almost invariably fatal without immediate surgical intervention.¹⁶ In marked contrast to the declining mortality rates associated with elective aneurysm repair, the 40–80 per cent mortality¹⁷⁻¹⁹ following ruptured aneurysm surgery in shocked patients has changed little over the past two decades. It is generally accepted that a significant reduction in mortality from ruptured abdominal aortic aneurysms will require better detection techniques and earlier surgical resection.^{20,21} Screening of patients at high risk for aneurysms – men

TABLE I Elective abdominal aortic aneurysm resection mortality rates (%)

1960–1969	9–18
1970–1975	4–9
1976–1986	1–6

The range of reported mortality rates for elective abdominal aortic aneurysm resection. (Composite figures from data reported in references 4–15).

over 55 years with other signs of peripheral vascular disease and first-degree relatives of aneurysm patients²² – may prove to be cost-effective. Recent data suggest that all aneurysms greater than 6 cm should be resected electively, regardless of the patient's age, unless there are severe medical contraindications.²³ Aneurysms less than 6 cm should be resected if the patient has a life expectancy of greater than five years. Contraindications to elective resection include a recent acute myocardial infarction, intractable angina pectoris, severe pulmonary insufficiency, chronic renal insufficiency or an associated disease with a life expectancy of less than two years.^{24–26} However, for such high-risk patients, a policy of serial ultrasound or computerized tomographic assessment at three-month intervals has permitted selective aneurysm resection in patients with significant or rapid expansion and symptom development.²⁷

Aorto-iliac reconstructive procedures employing either thrombo-endarterectomy, excision and graft replacement, or bypass were first introduced in the early 1950's.^{28–29} The initial series reported 30-day postoperative mortality rate of eight to nine per cent, which has declined to two to four per cent in recent series.^{30–31} Aortic reconstruction with replacement of a bifurcated aortofemoral or iliac graft in patients with aorto-occlusive disease is now a well-established surgical procedure with good postoperative outcome in terms of lower limb blood flow, relief of ischaemic symptoms and improved life expectancy. The current residual operative mortality for aortic vascular surgery is, in part, attributable to a high incidence of perioperative myocardial infarction and left ventricular failure in this patient population.³² Improved survival for electively resected aneurysms¹⁵ and aorto-iliac reconstruction,³⁰ in comparison with baseline mortality for non-operated patients, confirms the impression that aortic vascular surgery may effectively control the disease, may expand life expectancy and may be safely offered to almost all patients, whatever their age.³³

This review is confined to considerations involving elective abdominal aortic vascular procedures. The objectives of the review are to highlight the clinical characteristics of the patient population; to assess multivariate risk factor analysis and the invasive/non-invasive techniques available for risk factor identification and management in this high-risk surgical population; to assess the major haemodynamic, metabolic and regional blood flow changes associated with aortic cross clamping/unclamping procedures and techniques for their modification or attenuation; to contrast the haemodynamic changes observed during surgery for aortic aneurysm resection with surgery for aorto-iliac occlusive disease and to assess the influence of perioperative anaesthetic techniques and management on patient outcome.

TABLE II Abdominal aortic surgery – coexisting disease states

Heart disease	
Previous myocardial infarct	40–50
Angina	10–20
Congestive heart failure	10–15
Hypertension	50–60
Chronic obstructive pulmonary disease	25–50
Diabetes Mellitus	9–12
Renal impairment	5–17

The range of coexisting disease states (%) reported in association with abdominal aortic surgery. (Composite figures from data reported in references 9–10, 15, 30–41.)

Risk factor identification and management

Aneurysms and occlusive disease involving the abdominal aorta are due to atherosclerosis in over 90 per cent of patients.³⁴ It is now recognised that even the five to ten per cent of abdominal aortic aneurysms that were once reported to be associated with syphilis were nevertheless of atherosclerotic origin.¹⁹ Trauma, infection, Marfans Syndrome or Takayasu's disease may occasionally be implicated in degenerative changes in the arterial wall, especially in younger patients. The manifestations of atherosclerosis – ischaemic heart disease, aortic aneurysm formation, aorto-iliac and peripheral vascular occlusive disease, cerebrovascular disease – are all part of the same disease process which may begin at different times and progress at different rates throughout the arterial tree.³⁵

The high prevalence of co-existing coronary artery disease, hypertension, chronic obstructive pulmonary disease, diabetes and renal impairment in relatively elderly patients presenting for abdominal aortic surgery is well documented. Myocardial infarction is responsible for 40–70 per cent of the mortality associated with abdominal aortic surgery.^{13–15,36} A previous myocardial infarct, based on history and documented by ECG, and/or enzyme changes has been reported in 40–50 per cent of this patient population, while 50–60 per cent have hypertension, 10–20 per cent angina and 10–15 per cent signs of congestive cardiac failure at the time of admission^{9,10,15,37–40} (Table II). Consequently a thorough evaluation of the current cardiovascular status is essential.

History, physical examination and routine electrocardiogram may identify a low-risk patient sub-group. Patients without previous myocardial infarction, angina, diabetes, congestive heart failure and with a normal resting ECG have been reported to be at very low risk (<1 per cent) for major perioperative cardiac complications.^{41,42} The objectives of the various multifactorial risk index analysis, invasive and non-invasive tests are to identify high-risk patients, to determine the current

functional status of the coronary circulation and myocardial function and to control factors associated with increased morbidity and mortality following anaesthesia and surgery.

Multivariate risk factor analysis

The ASA classification identifies factors associated with increased perioperative risk in a general surgical population but does not specifically assess the risk of cardiac complications. The need to determine prospectively operative risk in aortic vascular surgery is paramount because of the high incidence of coronary artery disease and related perioperative mortality.

The risk of myocardial re-infarction and cardiac death is significantly higher in patients undergoing surgery within six months of sustaining a myocardial infarct. Pooled data from large studies conducted in the 1960s and 1970s indicate that re-infarction or cardiac death occurred in approximately 30 per cent of patients having surgery within three months of infarction and in 15 per cent of patients having surgery between three to six months following infarction.⁴³⁻⁴⁵ For patients having surgery more than six months following infarction a stable six per cent re-infarction rate applies. More recent data suggest that careful patient selection, optimal preoperative assessment, invasive haemodynamic monitoring and cardiovascular pharmacological support may be associated with a dramatic reduction in re-infarction rates and cardiac deaths. Rao *et al.*⁴⁶ reported re-infarction rates of 5.8 per cent and 2.3 per cent within 0-3 months and 3-6 months respectively following infarction. The risk of perioperative cardiac death is increased tenfold in patients aged over 70 years while all cardiac complications are more likely with major intra-abdominal, intra-thoracic and aortic vascular procedures.⁴⁷

In 1977 Goldman *et al.*⁴⁸ proposed a cardiac risk index (CRI) to estimate the probability of a life-threatening complication (ventricular tachycardia, cardiogenic pulmonary oedema and/or myocardial infarction) or death during or following non-cardiac surgery (Table III). By multivariate discriminant analysis, various independent correlates of life-threatening and fatal complications were identified and a score was assigned. Patients were classified as risk Class I to IV according to the total score. The most significant prognostic factors were signs of congestive cardiac failure, recent myocardial infarction, arrhythmias, and age greater than 70 years. Jeffrey *et al.*⁴⁹ evaluated 99 patients over 40 years of age having their first abdominal vascular procedure with preoperative cardiac risk index. The CRI grossly underestimated serious cardiovascular complications in Class I, while Class II and III reliably predicted outcome. The CRI

assigns a low score to the type of surgery performed, which may fail to reflect the profound haemodynamic derangements associated with aortic vascular surgery. Goldman recently used the multifactorial cardiac risk index to estimate the probability of cardiac complications in patients having abdominal aortic aneurysm surgery.⁵⁰ By multiplying the prior odds of complications by the likelihood ratio for each class, the approximate risk of major cardiac complications increased from three per cent in Class I to 75 per cent in Class IV patients.

Cooperman *et al.*⁴⁰ devised a scoring system of risk factors based on an evaluation of 566 patients undergoing vascular surgery. Using a chi-squared analysis technique, five major risk factors were identified - congestive cardiac failure, arrhythmias, prior myocardial infarction, prior stroke and an abnormal electrocardiogram. Angina was associated with increased, albeit statistically insignificant, risk of cardiovascular complications. Multivariate analysis of these six factors lead to the development of an equation which predicted the probability of a cardiovascular complication. Domaingue *et al.*⁵¹ compared the Goldman CRI with the Cooperman equation in patients having vascular surgery. Cooperman's scheme proved more accurate in assessing postoperative cardiac outcome.

The advantages of multivariate risk factor analysis are that the methods utilize standard clinical, ECG and roentgenographic findings, are inexpensive and are widely applicable to patient populations. The disadvantages are that individual asymptomatic patients with significant coronary artery disease may not be detected.

Invasive assessment

AUTOMATED PHYSIOLOGIC PROFILE

The automated physiologic profile (APP) system, described by Cohn *et al.*⁵² has been utilized the day before surgery to evaluate and prepare patients scheduled for major vascular procedures. Following pulmonary artery catheterization, a Sarnoff ventricular function curve is obtained by plotting left ventricular stroke work index against pulmonary capillary wedge pressure. Treatment consists of preload adjustment (volume/diuretics), inotropic support and afterload reduction initiated simultaneously or in sequence. A modification of the APP involves calculation of the upstroke or gradient of the ascending portion of the left ventricular function curve. Knight *et al.*⁵³ reported a significantly increased postoperative cardiac complication rate in patients with depressed upstroke compared with patients having normal upstroke on fluid challenge. Using the slope of the left ventricular

TABLE III Multivariate risk factor analysis
Multifactorial index of cardiac risk; Goldman *et al.*⁴⁸

History	
Myocardial infarction within 6 months	10
Age > 70 yrs	5
Physical examination	
S-3 or jugular venous distension	11
Important aortic stenosis	3
Electrocardiogram	
Rhythm other than sinus or sinus plus APB on last preoperative electrocardiogram	7
More than five premature ventricular beats per minute at any time before operation	7
Poor general medical status	3
Intraperitoneal, intrathoracic or aortic surgery	3
Emergency operation	4
Total	53

Computation of cardiac risk (PCOMP) according to Cooperman⁴⁰

X ₁	Angina
X ₂	Congestive cardiac failure
X ₃	Arrhythmia
X ₄	Myocardial infarction
X ₅	Cerebrovascular accident
X ₆	Abnormal electrocardiograph

PCOMP = ANTILOGE (0.46 X₁ + 1.02 X₂ + 0.62 X₃ + 0.64 X₄ + 1.15 X₅ + 1.25 X₆ - 3.81)
If a particular risk is present, then the corresponding X factor is replaced by 1. If absent, the X factor is replaced by 0.

Adjusted multifactorial index; Goldman⁵⁰

*Calculated by multiplying the prior odds of complications by the likelihood ratio for each class.

Type of patient	Approximate baseline major cardiac complications for this type of patient (%)	Approximate risk of major cardiac complications in this type of patient as adjusted using Multifactorial Index (%)			
		Class I	Class II	Class III	Class IV
Unselected consecutive patients older than 40 yr who have major non-cardiac surgery	4	1.2	4	12	48
Patients who have abdominal aortic aneurysm surgery or who are older than 40 yr and have high risk characteristics that generally generate medical consultations before major non-cardiac surgery	10	3	10	30	75

performance curve to optimize cardiac output, Whittemore *et al.*⁵⁴ have noted an impressive reduction in operative mortality rates. The logistics and costs involved in preoperative intensive care management may have prevented a more widespread application of the APP system since its development over a decade ago.

CORONARY ANGIOGRAPHY

Routine coronary angiography to determine the prevalence of severe coronary artery disease has been recommended for all patients under consideration for elective vascular reconstruction at the Cleveland Clinic since

1978.⁵⁵ Those found to have severe correctable coronary artery disease were advised to undergo myocardial revascularization before major vascular surgery. This and other Institutions⁵⁶ performing routine coronary angiography before abdominal vascular surgery reported that, of those patients considered clinically and electrocardiographically free of coronary artery disease, 15–30 per cent have greater than 70 per cent stenosis of one or more vessels. Following the initiation of a policy of routine coronary angiography, early encouraging reports highlighted low mortality rates in patients having elective aortic reconstruction following myocardial revascularization. How-

ever, recent Cleveland Clinic studies report a 5.7 per cent mortality rate among 70 coronary artery bypass grafts in patients with infrarenal aortic aneurysms. The incidence of aneurysm rupture after cardiac surgery was 2.9 per cent and mortality rates for aneurysm repair after bypass grafting was 1.8 per cent.⁵⁷ Routine preoperative coronary angiography was not associated with obvious clinical benefits at the Cleveland Clinic and is no longer standard practice.⁵⁸

Notwithstanding data from McCollum *et al.*,⁵⁹ Edwards *et al.*,⁶⁰ and Crawford *et al.*⁶¹ also claiming that patients undergoing coronary artery bypass grafting are acceptable risks for subsequent surgery and may have less cardiac risk than routine patients, the role of routine coronary angiography in the preoperative assessment of patients for elective vascular surgery remains controversial. Coronary angiography, while the most specific and sensitive assessment of coronary artery disease, may not be a widely applicable screening test for all patients scheduled for aortic vascular surgery because of inherent risk, cost and manpower implications. Brown *et al.*³² noted a mortality rate of 0.8 per cent from myocardial infarction in patients with no coronary artery disease and 2.9 per cent in patients with coronary artery disease having elective aortic vascular resection at their institution. The authors suggest that the risks inherent in coronary angiography, the overall 2.3 per cent mortality in myocardial revascularization surgery⁶² and the hazards of aneurysm rupture in the waiting period before or following revascularization does not justify the routine application of this preoperative management. The selective application of coronary angiography, in patients with positive preoperative non-invasive screening for coronary artery disease, may be a safer and more cost-effective means of lowering perioperative mortality.¹³

Non-invasive assessment

In recent years non-invasive methods employing ECG monitored exercise testing, echocardiography, radionuclide angiography and dipyridamole-thallium imaging have been extensively utilized to preoperatively assess cardiac performance.

EXERCISE TESTING

ECG-monitored exercise testing has been proposed as a cost-effective, easily applicable means of screening for asymptomatic coronary artery disease in patients presenting for major vascular surgery.⁶³ Cutler *et al.*⁶⁴⁻⁶⁵ noted that 30 per cent of these patients, with no previous history of myocardial infarction or angina and with a normal ECG, will manifest an ischaemic response during or following exercise. Proponents of exercise testing claim

that an ischaemic response – defined as 1 mm or greater ST segment depression, arrhythmia or intractable angina – is a useful predictor of perioperative cardiac complications.⁶⁶⁻⁶⁷ Patients able to achieve greater than 85 per cent of their predicted maximum heart rate at high maximal oxygen uptake may represent a low risk group for major vascular surgery.⁶⁸ The ability of vascular surgery patients to participate in exercise studies may be hampered by claudication, arthritis and amputation while digitalis, diuretic and beta-blocking agent administration may cause difficulties of interpretation.⁶⁹ In addition, limited sensitivity and low specificity have been reported for exercise testing. In patients with clinical evidence of coronary artery disease, stress testing only confirmed the high likelihood of an ischaemic response being observed while a negative test often proved falsely negative on subsequent coronary angiography.⁷⁰⁻⁷¹ Exercise testing may not substantially improve high-risk identification compared with standard resting ECG.⁷² The advent of more sensitive and specific screening tests of cardiac performance have relegated the importance of exercise testing in the preoperative assessment of major vascular surgery patients.

NUCLEAR CARDIOLOGY AND ECHOCARDIOGRAPHY

Radionuclide angiography (RNA)⁷³ and echocardiography⁷⁴ have proved accurate and reproducible means of global left ventricular ejection fraction (LVEF) determination compared with contrast ventriculography. Radionuclide studies, using stationary gamma cameras, and two dimensional (2D) echocardiography, are particularly useful in detecting the presence of regional ventricular wall asynergy or dyssynergy. The initial applications of cardiac radionuclide assessment to patients presenting for major vascular surgery were optimistic. Preoperative determination of cardiac function was reported to enhance the management and predict the need for pulmonary artery catheterization in patients presenting for aorto-bifemoral grafting.⁷⁵ Fiser *et al.*⁷⁶ demonstrated that preoperative resting, first-pass, LVEF correlates closely with the derived cardiac index the night before surgery. The two perioperative deaths among 20 patients studied occurred in patients with LVEFs less than 30 per cent. Resting RNA determination of ejection fraction was reported to predict perioperative myocardial infarction rates in patients presenting for abdominal aortic aneurysm resection⁷⁷ and lower limb revascularization.⁷⁸ No patients with ejection fractions >56 per cent sustained perioperative myocardial infarctions. Mosely *et al.*,⁷⁹ in a series of 41 patients having aortic surgery, reported three deaths of refractory cardiac failure in four patients with LVEF less than 30 per cent compared with 2.7 per cent in

FIGURE 1 Algorithm for patient management and surgical selection – abdominal aortic aneurysm resection.

those with LVEF greater than 30 per cent. Kazmers *et al.*⁸⁰ reported a cumulative mortality rate of 50 per cent in patients with LVEF <35 per cent compared with 14 per cent in those with LVEF >35 per cent over a 20.2 ± 11.9 -month study period.

In recent years the value of preoperative resting left ventricular ejection fraction in predicting left ventricular performance during elective aortic surgery has been questioned. Preoperative knowledge of left ventricular ejection fraction, as determined by multiple unit gated acquisition angiography (MUGA) scan, did not identify a subgroup of patients in whom PCWP and CVP correlated consistently throughout abdominal aortic surgery⁸¹ and proved only comparable to clinical assessment in predicting the need for pulmonary artery catheterization.⁸² RNA and 2D echocardiographic determination of LVEF did not identify a group of patients in whom left ventricular stroke work index (LVSWI) decreased significantly during aortic vascular surgery.⁸³

Resting radionuclide angiography may not be sufficiently sensitive to discriminate patients with normal

coronary arteries from those with significant coronary artery disease. Patients with generalised atherosclerosis or left main coronary artery stenosis may have normal left ventricular function and ejection fraction at rest but during exercise impaired ejection fraction may develop secondary to cardiac dilatation and hypokinesis.⁸⁴ Preoperative exercise radionuclide scanning may prove more informative in patients with coronary artery disease.⁸⁵ High sensitivity and specificity for exercise-RNA testing in patients with coronary artery disease were initially reported in the late 1970's.⁸⁶ The declining specificity of the test in recent years has been attributed to changing test population.⁸⁷ Exercise-RNA testing may predict perioperative mortality rate better and suggest further cardiac evaluation. A LVEF of less than 50 per cent at rest with abnormal myocardial contractility and/or less than five per cent ejection fraction increase following exercise should suggest surgical deferral pending coronary angiography.⁸⁸

Because of the difficulty in achieving adequate exercise stress in patients presenting for major vascular surgery, a

FIGURE 2 Algorithm for patient management and surgical selection — Aorto-iliac occlusive disease.

pharmacological technique may be employed to predict perioperative ischaemic events. Dipyridamole-induced maximum coronary vasodilation, in combination with thallium myocardial imaging, has a sensitivity and specificity for the detection of coronary disease comparable to that of exercise thallium imaging.⁸⁹ Thallium redistribution seen on serial images after dipyridamole is a marker for relative hypoperfusion of viable myocardium, whereas a persistent defect suggests the presence of infarcted myocardium.⁹⁰ Eagle *et al.*⁹¹ noted no ischaemic events in 43 patients without redistribution compared with eight ischaemic events in 18 patients with thallium redistribution. Thallium redistribution was found to have the best statistical correlation with postoperative myocardial infarction in a series of 116 patients referred for aortic reconstructive surgery.⁹² Dipyridamole-thallium-201 imaging may be the most ideal of the available screening tests.⁹³ Sensitivities of 85–93 per cent and specificities of 64–80 per cent in detecting significant coronary artery stenosis have been reported.^{89,94} Angina, headache dizzi-

ness and nausea have been noted in up to 40 per cent of patients following IV dipyridamole administration.⁸⁹ A 300 mg oral dipyridamole suspension may be substituted for IV dipyridamole if an intravenous drug preparation is not available.⁹⁵ The test is relatively safe, minimally invasive, cost effective and highly sensitive in detecting myocardial ischaemia in asymptomatic patients.

Management

Aggressive medical management, further cardiac evaluation and a modification or avoidance of the planned operative approach may be required if significant coronary artery disease and impaired myocardial function is detected on preoperative clinical evaluation and screening tests. Algorithms for patient management and surgical selection are presented in Figures 1 and 2. Class I patients with no angina, previous myocardial infarct, congestive heart failure, cerebro-vascular disease or diabetes and with a normal resting ECG may proceed to surgery with the expectation of very low cardiac risk.⁹⁶ Class II

patients with abnormalities on routine evaluation but no myocardial redistribution on dipyridamole thallium-201 scan should also proceed to surgery. Class III patients with clinical coronary artery disease and significant myocardial redistribution on dipyridamole thallium-201 scan should undergo coronary angiography. Prophylactic myocardial revascularization should be considered in the presence of left main coronary artery stenosis, significant three-vessel disease, two-vessel disease with disease of proximal left anterior descending (LAD) coronary artery, single-vessel disease affecting LAD proximal to the first septal perforator, and any lesion associated with severe depression of left ventricular function or ischaemia during stress testing.⁹⁷ This approach has been reported to reduce significantly the risk of perioperative infarction during the subsequent abdominal aortic surgery.⁹⁸

In the exceptional situation of a patient with severe coronary artery disease or unstable angina presenting with an expanding aneurysm or aortoiliac disease with a preanagrenous limb, a simultaneous myocardial revascularization and aortic reconstruction may be undertaken.⁹⁹ This combined approach has been reported to minimize mortality and morbidity compared with a two-staged procedure in these selected patients.¹⁰⁰ Myocardial revascularization may not be possible in patients with diffuse small-vessel coronary artery disease and poor left ventricular function. For such class IV high cardiac-risk patients, a conservative policy of serial three-monthly ultrasound or CT assessment may be adopted with selective resection for rapid aneurysm expansion or symptom development.²⁷ An alternative nonresective treatment, including ligation of the internal iliac arteries to induce thrombosis of the aneurysm and axillobifemoral bypass, may be employed.¹⁰¹ If resection is unavoidable, the cardiac risk may be reduced by pharmacological control of any associated congestive heart failure, angina, dysrhythmias or hypertension. Correction of associated electrolyte abnormalities; appropriate intraoperative haemodynamic monitoring and anaesthetic management and, if indicated, the use of intraoperative balloon assist¹⁰² or femoral vein–artery partial cardiopulmonary bypass,¹⁰³ may all contribute to a successful surgical outcome.

A variety of extra-anatomical bypasses and angioplastic techniques is available for the high cardiac risk patients with aortoiliac occlusive disease. A potentially less stressful axillo-femoral bypass may be substituted for aorto-bifemoral bypass, a crossover femoral for aorto-femoral bypass or a percutaneous transluminal angioplasty for a femoropopliteal bypass.¹⁰⁴ These extra-anatomical bypasses may also be associated with perioperative myocardial infarction. Inferior long-term patency

and limb salvage may follow extra-anatomical bypass compared with aortoiliac reconstruction.¹⁰⁵

Aortic cross-clamping and unclamping

Haemodynamic changes

Infrarenal aortic cross-clamping and unclamping is an integral component of abdominal aortic surgery. For surgery involving the descending thoracic aorta or for surgical repair of abdominal lesions extending above the renal arteries, a more proximal site of clamping will be necessary. The haemodynamic sequence of aortic cross-clamping will be influenced by the preoperative coronary circulation and myocardial function, the site of cross-clamp application, the intravascular volume, the anaesthetic technique and agents employed and the surgical pathology. The anticipated consequences of an abrupt aortic cross-clamping include an increased impedance to ventricular ejection (afterload), a decreased venous return (preload), with decreased velocity and shortening of myocardial muscle fibres.^{106,107} The haemodynamic consequences of aortic cross-clamping have been extensively evaluated in experimental and clinical studies. Clinical reports consistently have demonstrated a 15–35 per cent reduction in stroke volume and cardiac index, coupled with an increased arterial blood pressure and up to 40 per cent increase in systemic vascular resistance.^{37,108–110} The effect of abdominal aortic cross-clamping on venous return is a composite of complementary and opposing factors – diminished venous return due to exclusion of blood flow to the pelvis and lower extremities; a possible redistribution of blood flow from the inferior vena cava to the superior vena cava;¹¹¹ an increase in left ventricular end systolic and end-diastolic volumes¹¹² – and the underlying myocardial functional reserve or compliance.

MYOCARDIAL FUNCTION

The patient's preoperative cardiac status and myocardial reserve may exert a profound influence on the haemodynamic responses to aortic cross-clamping. Attia *et al.*¹¹³ noted two different haemodynamic responses to aortic cross-clamping. Patients clinically free of underlying atherosclerotic heart disease demonstrated a decrease in pulmonary artery, pulmonary capillary wedge and central venous pressures when the aorta was clamped while patients with clinical evidence of atherosclerotic heart disease responded to cross-clamping with an increased right- and left-sided filling pressures. Three out of ten patients in this series, with severe coronary artery disease, responded to cross-clamping with pulmonary capillary wedge pressure increases of seven mmHg or greater and ECG evidence of myocardial ischaemia. Carroll *et al.*¹¹⁴

reported that two out of 14 patients undergoing aortic vascular surgery responded to cross-clamping with significant elevation of pulmonary artery occlusion pressure. In one of these cases ECG evidence of myocardial ischaemia appeared. Gooding *et al.*¹¹⁵ confirmed that, in addition to increasing pulmonary capillary wedge pressure on cross-clamping, patients with coronary artery disease sustained a greater reduction in cardiac index compared with patients judged free of coronary artery disease. The different responses to cross-clamping in patients with and without coronary artery disease suggest that patients with impaired myocardial contractility or increased left ventricular end-diastolic volumes may be unable to mobilize the Frank Starling mechanism further and may proceed to develop myocardial ischaemia and left ventricular failure following abrupt increases in afterload.

Extensive evaluations of left ventricular function during aortic cross-clamping have been reported using systolic time intervals, nuclear ventriculography and two-dimensional transoesophageal echocardiography. Systolic time interval¹¹⁶ (STI) patterns characteristic of patients without evidence of previous myocardial infarction were lengthening of preejection period (PEP) and shortening of left ventricular ejection time (LVET). These changes were consistent with decreased preload. In patients with evidence of previous myocardial infarction, both PEP and LVEF lengthened, consistent with decreased left ventricular function. Perioperative nuclear ventriculography¹¹⁷ has demonstrated impaired myocardial performance (the relation between cardiac index and end-diastolic volume index) and systolic function (the relation between systolic blood pressure and the systolic volume index) suggesting impaired myocardial contractility following cross-clamping. The haemodynamic consequences of aortic cross-clamping may vary greatly depending on the site of clamp application. Two-dimensional transoesophageal echocardiographic studies¹¹⁸ reported significant increases in left ventricular end-systolic and end-diastolic volumes, decreases in ejection fraction and frequent wall motion abnormalities with clamping at the supraceliac level with only minor changes apparent at the infrarenal level.

The small bowel evisceration and mesenteric traction associated with transabdominal aortic reconstruction may be responsible for the observed decreased mean arterial pressure and systemic vascular resistance, increased cardiac index and heart rate, facial flushing, and a fourteen fold increase in 6-keto-PGF α , the stable metabolite of prostacyclin.¹¹⁹ Part of the reduction in cardiac output during aortic cross-clamping may reflect metabolic changes¹²⁰ and decreases in cross-clamping adapted body oxygen consumption and carbon dioxide production¹²¹. Experimental work suggests that aortic cross-clamping

causes prostaglandin (PG) of the E series to be secreted, which reduces aortic pressure, lowers systemic vascular resistance and increases cardiac output.¹²² Aortic unclamping, on the other hand, is associated with an elevated PGF,¹²³ which may attenuate the hypotension characteristic of the unclamping period. Utsunomiya *et al.*¹²⁴ studied the effects of prostacyclin (PGI₂) and thromboxane (Tx) in mediating depressed cardiac performance during elective abdominal aortic aneurysm resection. The surgical incision and retroperitoneal dissection are events related to PGI₂ production while thromboxane A₂ (TxA₂) synthesis is triggered by aortic cross-clamping. Thromboxane B₂ (TxB₂), the stable metabolite of TxA₂, increases following aortic cross clamping and is associated with a reduction in cardiac output.¹²⁵ In vitro testing of patients' plasma showed a reduction of Ca⁺⁺ ATPase and Mg⁺⁺ ATPase activity in myocardial sarcoplasmic reticulum in association with a depressed papillary muscle developed tension.¹²⁶ Cyclo-oxygenase inhibition with aspirin or ibuprofen before surgery may prevent myocardial contractility depression and may maintain a stable cardiac output following cross clamping in patients with adequate intravascular volume.¹²⁷

ABDOMINAL AORTIC ANEURYSM AND AORTO-OCCLUSIVE DISEASE

The extent of collateral circulatory changes in patients with aorto-iliac occlusive disease has been proposed as the mechanism for a different haemodynamic response to aortic cross clamping compared with patients with abdominal aortic aneurysms. These studies noted a tendency for less marked haemodynamic changes – an unchanged cardiac index, stroke volume and systemic vascular resistance – compared with significant changes during aortic aneurysm resections.¹²⁸ Chronic collateral circulation associated with aorto-occlusive disease may permit continuous lower extremity perfusion during aortic cross clamping. Johnston *et al.*¹²⁹ postulate that the amount of collateral vascularization seen on the preoperative aortograms may selectively predict the magnitude of change in stroke volume and systemic vascular resistance that will occur intraoperatively on cross-clamp application. Minimal elevations in serum lactate concentration have been proposed to explain the stable haemodynamic and metabolic effects observed following aortic declamping. Conflicting data suggest that the haemodynamic changes on cross-clamping and declamping may be similar in both groups.^{108,117,130} Differences in patients' ages, myocardial function, anaesthetic techniques, aortic cross-clamping time and intraoperative fluid regimens may account for the different haemodynamic responses observed in the aortic aneurysm and aorto-occlusive patients in the studies quoted.

AORTIC UNCLAMPING

During infrarenal aortic cross-clamping the lower extremities and pelvis undergo ischaemic vasodilatation and vasomotor paralysis. Although systemic vascular resistance and arterial blood pressure decrease following unclamping,^{108,109} the consequent change in cardiac output is critically dependent on the intravascular volume at the time of cross-clamp release. The magnitude and direction of the cardiac output change, and the regional increased flow to the lower extremities and pelvis may cause diversion of blood flow from the critical coronary, renal and hepatic vascular beds. Perry,¹³¹ in a classic experimental and clinical study, first highlighted the extent of blood sequestration in the previously ischaemic lower extremities. Restoration of circulating blood volume and gradual restoration of blood flow to the distal vessels prevented significant reductions in blood pressure and cardiac output. Lactic acid and products of anaerobic metabolism accumulate in ischaemic tissues during cross-clamping.¹³² Declamping hypotension may result from hypovolaemia (pooling of blood in capacitance vessel), and the release of vasoactive metabolites and myocardial depressant factors.¹³³ Plasma adenosine, inosine, hypoxanthine and xanthine concentrations increase after cross-clamp removal and these plasma purine degradation products have been implicated in the aetiology of declamp hypotension and renal vasoconstriction.¹³⁴ Diastolic compliance (the relation between pulmonary capillary wedge pressure and end-diastolic volume index) may decrease after declamping, indicating myocardial dysfunction.¹¹⁷ Prevention of declamping hypotension and maintenance of a stable cardiac output is best achieved by volume loading to a higher than preoperative pulmonary capillary wedge pressure prior to the cross-clamp release.¹¹⁰

Changes in cardiac output following declamping may differ in patients undergoing aorto-bifemoral grafting for occlusive arterial disease. Cardiac output has been shown to decrease following declamping in animal experiments^{131,132} and in patients undergoing aortic aneurysm resection.^{109,110} In contrast, well hydrated patients with aorto-occlusive disease increase their cardiac output following unclamping.¹²⁹ Following revascularization for aortoiliac occlusive disease, reactive hyperaemia of the lower limb may not occur at the time of declamping but will develop gradually over several hours.¹³⁵

Regional circulation

The kidney

Acute renal failure has been frequently reported following surgery involving infrarenal aortic cross-clamping. Despite improvements in patient selection, anaesthetic man-

agement and surgical techniques, a 0.2–3 per cent incidence of acute renal failure following elective surgery has been reported.^{136,137} Despite aggressive management, mortality rates approaching 25 per cent may follow. Diminished preoperative renal function,¹³⁸ advanced age,¹³⁹ iodinated contrast material injection,¹⁴⁰ inadequate balanced salt replacement for the extracellular fluid deficit caused by angiography, mechanical bowel preparation and fasting may all contribute to impaired renal function following surgery.¹⁴¹ Occasionally a unilateral or bilateral ureteric obstruction will result from encasement in the aneurysm wall and stenosis of one or both renal arteries may require resection.⁶⁶ It has been suggested that preoperative renal ultrasound or an excretory urogram should be obtained to detect any ureteral obstruction or distortion produced by the aneurysm; to determine the excretory function of the two kidneys and to ensure that horseshoe kidney will not be encountered unexpectedly at surgery.¹⁴²

Inconclusive experimental and human studies have been published on the effects of infrarenal aortic cross-clamping on renal perfusion and intrarenal blood flow distribution. Early animal experiments¹⁴³ demonstrated acute tubular necrosis, which was attributed to aortic cross-clamping per se and was reversed by direct or pharmacological renal nerve blockade. Using Xenon¹³³ washout techniques to measure the distribution of intrarenal blood flow, Abbott *et al.*¹⁴⁴ demonstrated decreased cortical blood flow during aortic cross-clamping. Gamulin *et al.*¹⁴⁵ demonstrated profound and sustained alterations in renal haemodynamics using ⁵¹CrEDTA and ¹²⁵I Hippuran clearance techniques. Despite stable cardiovascular variables, infrarenal aortic cross-clamping was associated with a 38 per cent decrease in renal blood flow and a 75 per cent increase in renal vascular resistance. Renal sympathetic blockade induced by T6 epidural anaesthesia did not prevent the renal vasoconstriction or the impaired renal haemodynamics and function following infrarenal aortic cross-clamping.¹⁴⁶ The observed renal dysfunction may be associated with increased plasma renin activity, renal prostaglandins, kallikrein or unknown intrinsic mechanisms. Other investigators have failed to demonstrate a detrimental effect of infrarenal cross-clamping on renal perfusion and distribution of flow.¹⁴⁷ Microsphere renal studies have demonstrated no change in the distribution of renal blood flow if adequate intravascular volume and a stable cardiac output are maintained.¹⁴⁸ Failure to standardise species and study methods, cardiovascular variables and intravenous hydration have not facilitated comparisons of published data.

Predisposing causes of acute renal failure following aortic vascular surgery include hypotension, large volume blood transfusion, atheromatous plaque embolization to

renal arteries, intravascular myoglobin and other by-products of muscle ischaemia and suprarenal aortic cross-clamping with warm ischaemic time.¹⁴⁹ The role of diuretic therapy to improve renal perfusion or minimize nephrotoxic effects is controversial. Mannitol, an osmotic diuretic, may be beneficial in preserving renal function in aortic surgery when transient hypovolaemia develops.¹⁵⁰ High-dose mannitol may improve renal cortical flow,¹⁵¹ may reduce renal cell swelling following total ischaemia and, in the presence of a contracted intravascular volume, may prevent sludging of cellular debris in the renal tubules.¹⁵² The loop diuretics transiently increase free water and sodium excretion in the face of renal ischaemia. In addition, they increase renal blood flow by stimulating the release of intrarenal prostaglandin E (PGE), a potent dilator of the afferent renal arterioles.¹⁵³ Combinations of mannitol, dopamine and furosemide have been advocated to prevent renal dysfunction during aortic vascular surgery. However, much of the data supporting the proposed benefit of these measures come from animal experiments in which deliberate extracellular fluid expansion was not employed. Paul *et al.*¹⁵⁴ were unable to demonstrate a clinically important benefit from the use of mannitol and dopamine compared with extracellular fluid volume expansion with saline alone in patients undergoing elective infrarenal aortic cross-clamping. Significant transient decreases in glomerular filtration rate were observed in the early and late post-clamp release period, despite maintenance of haemodynamic stability.

Careful preoperative screening and management are essential. Recent data suggest that patients with mild renal dysfunction (serum creatinine less than $4 \text{ mg} \cdot \text{dl}^{-1}$) can undergo elective aneurysm resection without additional mortality.¹⁵⁵ Preoperative haemodialysis should be considered for patients with severe renal dysfunction (serum creatinine greater than $4 \text{ mg} \cdot \text{dl}^{-1}$) to help reduce the high incidence of serious postoperative renal function deterioration and subsequent mortality. A balanced salt solution infusion preoperatively to replace extracellular fluid deficit associated with fasting, angiography and bowel preparation coupled with aggressive and prompt intraoperative hydration and blood loss replacement, guided by pulmonary capillary wedge pressure measurements, will best ensure adequate urine output and normal renal function following abdominal aortic surgery.¹⁵⁶

The spinal cord

Spinal cord damage associated with aortic vascular surgery may follow translumbar abdominal aortography or untoward events during the surgical intervention. In an extensive review of 3,164 procedures with temporary occlusion of the abdominal aorta, Szilagyi *et al.*¹⁵⁷

reported a 0.25 per cent incidence of spinal cord damage following abdominal aortic surgery and a 0.01 per cent incidence following translumbar aortography. The incidence of spinal cord damage was ten times more prevalent in ruptured compared with unruptured aneurysms and no spinal cord damage was associated with surgery for aorto-iliac occlusive disease. The most common neurological deficits noted were complete flaccid paraplegia with dissociated sensory loss. Spinal cord ischaemia and paraplegia following thoraco-abdominal aortic aneurysm resection have been variously attributed to increased cerebrospinal fluid pressure associated with hypertension proximal to the cross-clamping site,¹⁵⁸ the site and duration of cross-clamp application,¹⁵⁹ intraoperative hypotension¹⁶⁰ and accidental permanent interruption of critical lower intercostal and lumbar arteries. However, recent conflicting experimental studies have reported no relationship between spinal cord damage and arterial blood pressure, and intracranial or intraspinal pressure.¹⁶¹

The major radicular arterial supply of the caudad spinal cord has been termed the great radicular artery or the artery of Adamkiewicz. Angiographic studies have localized the origin of this vital radicular artery to the T9–T12 level in the majority of patients.¹⁶² The great radicular artery may be inadvertently interrupted when aortic cross-clamps are placed either just below the renal arteries or between the diaphragm and renal arteries, in the absence of well developed infrarenal anastomatic communications. Somatosensory cortical evoked potential monitoring (SSEP) has been recommended to detect and minimize spinal cord ischaemia during thoracic aortic surgery.¹⁶³ Unfortunately, this technique has the relative disadvantage of reflecting primarily dorsal column function, with no direct assessment of anterior cord function.¹⁶⁴ Specifically, ischaemic changes of anterior cord function during aortic cross-clamping may be associated with complete motor loss and preservation of SSEP. This consideration has limited the application of SSEP monitoring during thoracic aortic aneurysm surgery.¹⁶⁵

Motor evoked potentials (MEP) are currently under investigation as a direct means of monitoring anterior spinal cord function. Theoretically, monitoring of MEPs by direct stimulation of the spinal cord over the major tracts¹⁶⁶ or transcranial stimulation over the motor cortex¹⁶⁷ or precise examination of spinal evoked potentials¹⁶⁸ may be possible. Unfortunately, if MEPs are to be monitored by recording muscle activity, neuromuscular blockade must be allowed to dissipate. To date, no epileptic activity has been triggered by this technique. However, percutaneous cortical stimulation is uncomfortable and produces increases in heart rate and blood pressure in awake volunteers and anesthetized patients.

Selective preoperative angiography and anomalous vessel reimplantation have been advocated to reduce the incidence of spinal cord ischaemia associated with elective abdominal aortic surgery. Such additional measures are unwarranted because of the infrequent association of spinal cord damage with elective abdominal aortic aneurysm resection and surgery for aorto-iliac occlusive disease. Difficulties and risks are involved in selective lumbar artery catheterization to visualize the arteria radicularis magna and technical hazards are associated with attempted lumbar artery reimplantation into the aortic graft. Intraoperative monitoring of anterior spinal cord function is, at present, imprecise and the risk/benefit ratio in this patient population has yet to be established.

Intestine

Over 101,000 abdominal aortic reconstructive procedures are performed each year in the United States.¹⁶⁹ In the majority of these procedures the inferior mesenteric artery, the primary arterial supply of the descending and sigmoid colon is sacrificed. Following inferior mesenteric artery ligation, collateral flow from the splenic flexure to mid-rectum should come from the mid-colic branch of the superior mesenteric artery and the haemorrhoidal branches of the hypogastric vessels. Ischaemic colitis is a well recognized complication of abdominal aortic surgery. Small bowel ischaemia has been reported in aorto-occlusive patients when atherosclerotic coeliac and superior mesenteric arteries were further compromised by division of the inferior mesenteric.¹⁷⁰ Temporary infrarenal aortic occlusion is associated with a significant reduction in intestinal blood flow due to autoregulatory vasoconstriction.¹⁷¹ Nitroglycerin administration for afterload reduction may exacerbate the reduction in intestinal blood flow by shunting blood flow from the colonic mucosa.¹⁷² In contrast, a $15\text{--}50\text{ }\mu\text{g}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ sodium nitroprusside infusion, maintaining a 30 per cent mean arterial blood pressure reduction, was reported to restore splanchnic blood flow during experimental aortic cross-clamp studies.¹⁷³ Retrospective studies¹⁷⁴ suggest that one to two per cent of patients undergoing elective abdominal aortic surgery develop ischaemic lesions of the descending colon, consisting of reversible circumferential mucosal oedema and haemorrhage. Pseudomembranous erosions and ulceration are observed in more advanced cases. Perforation of gangrenous necrotic segments may be associated with 40–75 per cent mortality rates.¹⁷⁵ Colonic mucosal injury is usually associated with self-limiting diarrhoea while colonic mucosal and muscularis injury produce bloody diarrhoea and occasional stricture formation. Prospective studies employing postoperative endoscopic examinations^{176,177}

suggest the true incidence of ischaemic colitis following elective abdominal aortic surgery may be as high as six per cent. Improper inferior mesenteric artery ligation, operative trauma to the colon, hypotension and low cardiac output states, failure to restore hypogastric arterial flow and congenital absence of communicating collaterals between mesenteric and systemic vessels have all been implicated in the aetiology of ischaemic colitis. Prevention of ischaemic colitis may involve selective preoperative angiographic assessment of patients with a history suggestive of intestinal angina or physical findings of abdominal bruits. A large meandering mesenteric artery is indicative of an occlusive process in the superior or inferior mesenteric artery. At the time of surgery, ligation of the inferior mesenteric artery close to the aorta will preserve collateral circulation between the left coliac artery and the superior sigmoidal artery. Alternatively, reconstruction of the inferior mesenteric artery may be required. Prophylactic measures against stress ulceration should be routinely employed because of the established association between abdominal aortic aneurysm and peptic ulceration¹⁷⁸ and the complications of gastrointestinal bleeding and peptic ulceration associated with elective resection.¹⁷⁹

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Résumé

Les candidats à une chirurgie de l'aorte abdominale présentent souvent une athérosclérose généralisée, avec hypertension et atteinte des circulations coronaires et cérébrales, de même qu'un cortège de problèmes d'ordre pulmonaire, rénal ou métabolique. On peut détecter les atteintes coronariennes importantes et évaluer la fonction myocardique par l'examen clinique, l'électrocardiogramme, la radiographie pulmonaire, la ventriculographie isotopique au repos et à l'effort et la scintigraphie au thallium avec dipyridamole. Si l'examen physique, les examens de routine et la scintigraphie sont normaux, le risque de problème cardiaque en péri-opératoire est faible. Cependant, les coronariens que ont une redistribution importante à la scintigraphie au thallium avec dipyridamole devraient subir une angiographie et possiblement une revascularisation coronaire avant leur chirurgie aortique. Pour ceux d'entre eux qui se présentent avec un anévrisme de l'aorte abdominale et dont les coronaires sont inopérables, une attitude attentiste avec réévaluation trimestrielle par échographie ou tomographie axiale est justifiable, la résection étant réservée aux lésions symptomatiques ou en expansion rapide. De même, diverses techniques d'angioplastie peuvent être utilisées pour les lésions aorto-iliaques obstructives quand le risque cardiaque est élevé. Le clampage de l'aorte cause souvent une diminution du volume d'éjection, de l'index cardiaque et de la consommation en oxygène du myocarde avec augmentation de la résistance vasculaire systémique et peut produire en plus, chez les coronariens, une élévation de la pression capillaire pulmonaire de même que des signes électrocardiographiques d'ischémie. Ceux qui ont une histoire d'angine ou d'infarctus du myocarde, des signes de défaillance cardiaque, une fraction d'éjection diminuée ou de l'hypokinésie à la ventriculographie ou de la redistribution à la scintigraphie myocardique, sont les plus susceptibles de bénéficier d'un cathétérisme de l'artère pulmonaire. L'usage grandissant de l'échographie trans-oesophagienne bi-dimensionnelle et de la cardiographie isotopique en per-opératoire permettront de mesurer les diamètres, mouvements et performances du ventricule gauche. Vous trouverez un guide sur la conduite de l'anesthésie. Avec une anesthésie combinant opiacés, oxygène et agents inhalatoires, on produit une certaine hypodynamie cardiaque tout en protégeant l'apport d'oxygène au myocarde. Toutefois, chez ce type de patient, on évitera si possible le protoxyde d'azote et l'isoflurane à cause des risques d'ischémie. On utilisera une perfusion de nitrates si le clampage aortique cause de l'ischémie ou une baisse de la contractilité du myocarde. Par une hydratation adéquate en

pré-opératoire, un remplacement rapide des pertes sanguines et liquidiennes guidé par un monitoring serré en per-opératoire assurant la stabilité du débit cardiaque et une bonne technique chirurgicale, on pourra le mieux préserver les perfusions rénales, médullaires et mésentériques pendant la période péri-opératoire. Par ailleurs, la meilleure prévention d l'hypertension post-opératoire et de ses risques d'ischémie et d'infarctus du myocarde, demeure un bon contrôle de l'hypertension en pré-opératoire. On a récemment établi la relative sûreté de l'anticoagulation induite après l'insertion d'un cathéter péri-dural, cependant les avantages de la combinaison de techniques régionales et générales restent à démontrer.