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Abdominal Aortic Surgery: Anesthetic Implications

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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 hemodynamic, metabolic, and regional blood flow changes associated with aortic cross-clamping/unclamping procedures and techniques for their modification or attenuation; and to assess the influence of perioperative anesthetic techniques and management on patient outcome.

INTRODUCTION

The principles of surgical technique and anesthetic management have progressed dramatically since the first reported successful abdominal aortic aneurysm resection in the early 1950s [1]. At that time, the detection of an asymptomatic infra-renal abdominal aortic aneurysm was associated with a 50 percent mortality rate within the first year of diagnosis, 81 percent within five years, and 100 percent within eight years [1]. Operative mortality rates of 9–18 percent for elective aneurysm resection were reported in the 1960s [2]. The 4–9 percent operative mortality quoted in the early 1970s represented a substantial improvement in outcome [3]. In the past decade, a further decline in the 30-day operative mortality to 1–6 percent has become apparent (Table 1) [4]. Factors contributing to reduced operative mortality include improved surgical techniques, earlier surgical intervention, better patient selection and pre-operative management, improved imaging techniques, a greater understanding of the underlying vascular pathophysiology, advances in hemodynamic monitoring, improved anesthetic agents and techniques, and intensive post-operative care.

Patient outcome following abdominal aortic surgery will depend on age, presence and extent of co-existing disease states (especially cardiovascular), and surgical considerations (occlusive/aneurysmal disease). The high perioperative and long-term morbidity and mortality associated with major vascular surgery is related to the presence of ischemic heart disease and perioperative hemodynamic stresses. Long-term prognosis relates to the stability of the ischemic heart disease and the degree of ventricular dysfunction.

RISK FACTOR IDENTIFICATION AND MANAGEMENT

Aneurysms and occlusive disease involving the abdominal aorta are due to atherosclerosis in over 90 percent of patients. The manifestations of atherosclerosis—ischemic heart disease, aortic aneurysm formation, aorto-iliac and peripheral vascu-

Abbreviations: CI: cardiac index CRI: cardiac risk index CT: computed tomography CVP: central venous pressure ECG: electrocardiogram LVEF: left ventricular ejection fraction LVSWI: left ventricular stroke work index MUGA: multiple unit gated acquisition PCWP: pulmonary capillary wedge pressure RNA: radionuclide assessment SVR: systemic vascular resistance

TABLE 1
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 [4–15])

lar 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 [5]. Recent studies have established a familial association with abdominal aortic aneurysm formation. Investigations are currently attempting to establish the biochemical markers and underlying genetic basis for aneurysm development [6]. Interest to date has focused on the role of collagenase, elastase, and deficiencies of alpha-1-antitrypsin and copper.

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 percent of the mortality associated with abdominal aortic surgery [7]. A previous myocardial infarct, based on history and documented by electrocardiogram and/or enzyme changes, has been reported in 40–50 percent of this patient population, while 50–60 percent have hypertension, 10–20 percent have angina, and 10–15 percent have signs of congestive cardiac failure at the time of admission (Table 2) [8]. Recent (less than six months) myocardial infarction and current congestive heart failure are the only two consistent pre-operative predictors of perioperative cardiac morbidity. The value of other historical predictors, e.g., angina, hypertension, old infarct, and diabetes mellitus, is still unresolved.

A thorough evaluation of the current cardiovascular status is essential. History, physical examination, and routine electrocardiogram may identify a low-risk patient

TABLE 2
Abdominal Aortic Surgery: Co-Existing 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 (%) reported in association with abdominal aortic surgery (composite figures from data reported in [9,10,15,30–41]) subgroup. Patients without previous myocardial infarction, angina, diabetes, or congestive heart failure, and with a normal resting electrocardiogram (ECG) have been reported to be at very low risk (<1 percent) for major perioperative cardiac complications [9]. The objectives of the various multifactorial risk index analyses and 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 anesthesia and surgery.

MULTIVARIATE RISK FACTOR ANALYSIS

In 1977, Goldman et al. [10] proposed a cardiac risk index (CRI) to estimate the probability of a life-threatening complication (ventricular tachycardia, cardiogenic pulmonary edema, and/or myocardial infarction) or death during or following non-cardiac surgery. 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. [11] evaluated the pre-operative cardiac risk index in 99 patients over 40 years of age having their first abdominal vascular procedure. The CRI grossly underestimated serious cardiovascular complications in class I, while classes 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 hemodynamic derangements associated with aortic vascular surgery. The Goldman cardiac risk index may correlate with long-term survival in patients undergoing elective abdominal aortic surgery. Recent data highlighted the adverse survival associated with CRI class III–IV status, cardiac and cerebrovascular disease, and renal impairment in long-term follow-up studies [12]. Goldman recently used the multifactorial cardiac risk index to estimate the probability of cardiac complications in patients having abdominal aortic aneurysm surgery [13]. By multiplying the prior odds of complications by the likelihood ratio for each class, the approximate risk of major cardiac complications increased from 3 percent in class I to 75 percent in class IV patients.

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

Coronary Angiography

Routine coronary angiography to determine the presence of severe coronary artery disease has been recommended for all patients under consideration for elective vascular reconstruction at the Cleveland (Ohio) Clinic since 1978. Those found to have severe, correctable coronary artery disease were advised to undergo myocardial revascularization before major vascular surgery. This and other institutions performing routine coronary angiography prior to abdominal vascular surgery reported that, of those patients considered clinically and electrocardiographically free of coronary artery disease, 15–30 percent have greater than 70 percent 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. Recent Cleveland Clinic studies, however, report a 5.7 percent mortality rate among 70 coronary artery bypass grafts in patients with infra-renal aortic aneurysms. The incidence of aneurysm rupture after cardiac surgery was 2.9 percent, and the mortality rate for aneurysm repair after bypass grafting was 1.8 percent. Routine pre-operative coronary angiography was not associated with obvious clinical benefits at the Cleveland Clinic and is no longer standard practice [14].

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. The selective application of coronary angiography in patients with positive pre-operative non-invasive screening for coronary artery disease may be a safer and more cost-effective means of lowering perioperative mortality.

NON-INVASIVE ASSESSMENT

In 1984, the first of a series of studies addressed the prognostic value of specialized pre-operative cardiac testing. Exercise stress testing, Holter monitoring, and radionuclear and dipyridamole-thallium imaging were all evaluated over the next six years and were variously advocated for use in patients undergoing major vascular surgery. The results are, however, preliminary, and the efficacy/cost-effectiveness of these procedures remains controversial.

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. Cutler et al. [15] noted that 30 percent of patients with no previous history of myocardial infarction or angina and with a normal ECG will manifest an ischemic event during or following exercise. Proponents of exercise testing claim that an ischemic response—defined as 1 mm or greater ST-segment depression, arrhythmia, or intractable angina—is a useful predictor of perioperative cardiac complications. Patients able to achieve greater than 85 percent of their predicted maximum heart rate at high, maximal oxygen uptake may represent a low-risk group for major vascular surgery. 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 ECG interpretation. In addition, limited sensitivity and low specificity have been reported for exercise testing. The advent of more sensitive and specific screening tests of cardiac performance have diminished the importance of exercise testing in the pre-operative assessment of major vascular surgery patients.

Ambulatory ECG Monitoring

Ambulatory electrocardiographic monitoring is a reliable method for detecting myocardial ischemia, and preliminary evidence suggests that ischemia detected by ambulatory monitoring independently predicts the risk of cardiac events in patients with stable and unstable angina pectoris [16]. Recent data suggest that pre-operative ambulatory ECG monitoring used to detect episodes of myocardial ischemia is a useful assessment of cardiac risk in patients undergoing major vascular surgery; in particular, the absence of myocardial ischemia during monitoring indicates a very low operative risk [17].

Nuclear Cardiology and Echocardiography

The initial application of cardiac radionuclide assessment (RNA) to patients presenting for major vascular surgery was optimistic. Resting RNA determination of left ventricular ejection fraction (LVEF) was reported to predict perioperative myocardial infarction rates in patients presenting for abdominal aortic aneurysm resection and lower limb revascularization. No patients with LVEF > 56 percent sustained perioperative myocardial infarctions [18]. Kazmers et al. [19] reported a cumulative mortality rate of 50 percent in patients with LVEF < 35 percent compared with 14 percent in those with LVEF > 35 percent over a 20.2 ± 11.9 months' study period.

In recent years, the value of pre-operative resting LVEF in predicting left ventricular performance during elective aortic surgery has been questioned. Pre-operative knowledge of LVEF, as determined by multiple unit gated acquisition angiography (MUGA) scan, did not predict the hemodynamic performance during abdominal aortic surgery [20]. Recent data suggest that resting ejection fraction is a poor predictor of perioperative myocardial infarction in patients undergoing major vascular surgery [21].

Resting radionuclide angiography may not be sufficiently sensitive to discriminate between patients with normal coronary arteries and those with significant coronary artery disease. Pre-operative exercise radionuclide scanning may prove more informative in patients with coronary artery disease. Exercise-RNA testing may better predict the perioperative mortality rate and suggest further cardiac evaluation. An LVEF of less than 50 percent at rest with abnormal myocardial contractility and/or an increase of LVEF of less than 5 percent following exercise should suggest surgical deferral, pending coronary angiography [22].

Dipyridamole-Thallium Scanning

Because of the difficulty in achieving adequate exercise stress in individual patients presenting for major vascular surgery, a pharmacological technique may be employed to predict perioperative ischemic 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. 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. Sensitivities of 85–93 percent and specificities of 64–80 percent in detecting significant coronary artery stenosis have been reported. The test is relatively safe, minimally invasive, cost-effective, and highly sensitive in detecting myocardial ischemia in asymptomatic patients [23,24].

KEY POINTS FOR CLINICAL PRACTICE: PATIENT 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 pre-operative clinical evaluation and screening tests. An algorithm for patient management and surgical selection is presented in Fig. 1.

Class I patients with no angina, previous myocardial infarct, congestive heart failure, cerebrovascular disease, or diabetes and with a normal resting ECG may proceed to surgery with the expectation of very low cardiac risk.

Class II patients with abnormalities on routine evaluation but no myocardial redistribution on dipyridamole-thallium 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 with a view to prophylactic myocardial revascularization. This approach has been reported to reduce significantly the risk of perioperative infarction during the subsequent abdominal aortic surgery [25].

Class IV patients with non-correctable coronary artery disease: myocardial revascularization may not be possible in patients with diffuse small vessel coronary artery disease and poor left ventricular function. For such high cardiac-risk patients, a conservative policy of serial three-monthly ultrasound or computed tomography (CT) assessment may be adopted, with selective resection of rapidly expanding aneurysms or if symptoms develop [26].

INTRA-OPERATIVE MANAGEMENT: AORTIC CROSS-CLAMPING AND UNCLAMPING—HEMODYNAMIC CHANGES

The hemodynamic consequence of aortic cross-clamping will be influenced by the pre-operative coronary circulation and myocardial function, the site of cross-clamp application, the intravascular volume, the anesthetic 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), and decreased velocity and shortening of myocardial muscle fibers. The hemodynamic consequences of aortic cross-clamping have been evaluated extensively in experimental and clinical studies. Clinical reports consistently have demonstrated a 15–35 percent reduction in stroke volume and cardiac index, coupled with an increased arterial blood pressure and up to 40 percent increase in systemic vascular resistance [27].

Myocardial Function

The patient's pre-operative cardiac status and myocardial reserve may exert a profound influence on the hemodynamic responses to aortic cross-clamping. 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 further the Frank-Starling mechanism and may develop myocardial ischemia 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 transesophageal echocardiography. Perioperative nuclear ventriculography has demonstrated impaired myocardial performance (the relationship between cardiac index and end-diastolic volume index) and systolic function (the relationship between systolic blood pressure and the systolic volume index), suggesting impaired myocardial contractility following cross-clamping. The hemodynamic

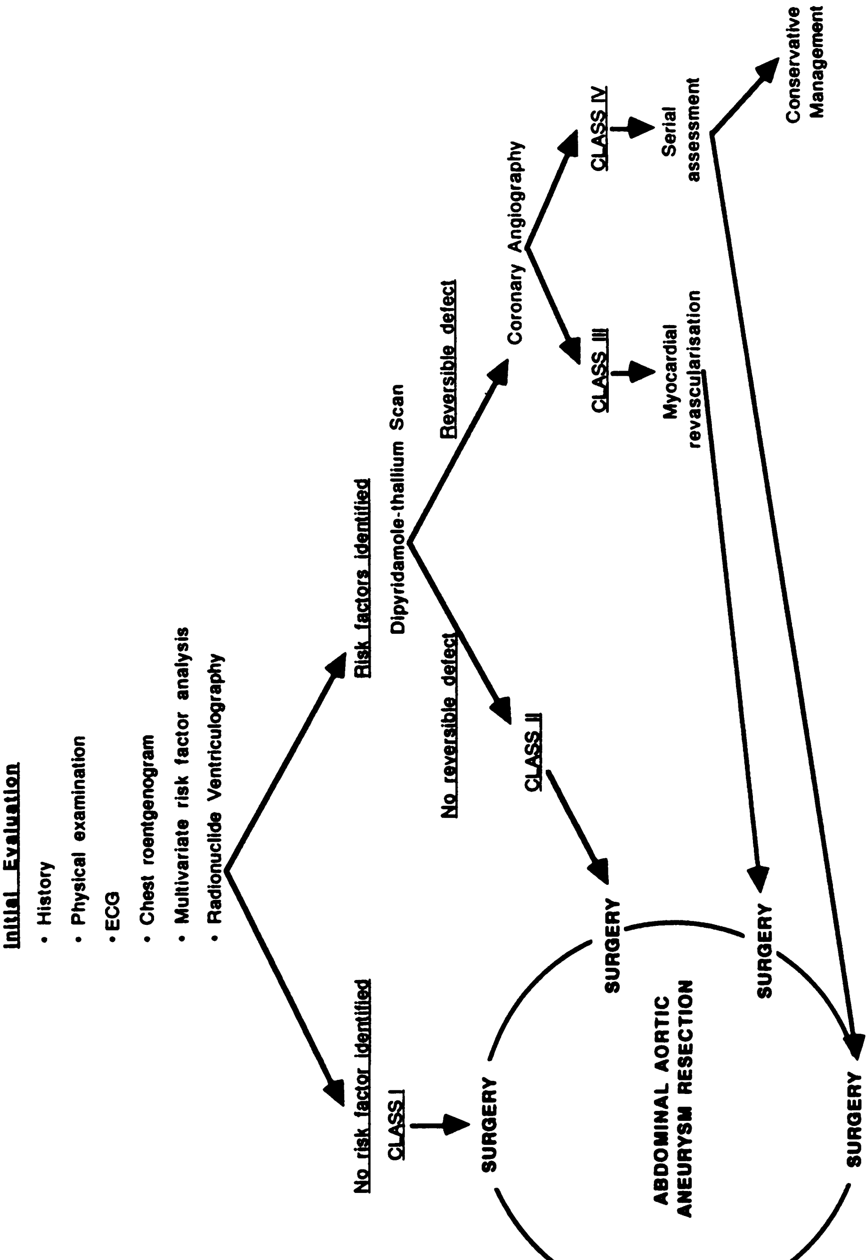

FIG. 1. Algorithm for patient management and surgical selection.

consequences of aortic cross-clamping may vary greatly, depending on the site of clamp application. Two-dimensional transesophageal echocardiographic studies 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 supra-celiac level; only minor changes were apparent when clamping at the infra-renal level [28]. The extent of collateral circulatory changes in patients with aorto-iliac occlusive disease has been proposed as the mechanism for a different hemodynamic response to aortic cross-clamping, compared to patients with abdominal aortic aneurysms [29].

Aortic Unclamping

During infra-renal aortic cross-clamping, the lower extremities and pelvis undergo ischemic vasodilatation and vasomotor paralysis. Although systemic vascular resistance and arterial blood pressure decrease following unclamping, the consequent changes in cardiac output are dependent on the intravascular volume at the time of cross-clamp release. The magnitude and direction of the cardiac output changes, and the increased blood flow to the lower extremities and pelvis may cause diversion of flow from the critical coronary, renal, and hepatic vascular beds. Unclamping hypotension may result from hypovolemia (pooling of blood in capacitance vessels), and from the release of vasoactive and myocardial depressant metabolites. Prevention of unclamping hypotension and maintenance of a stable cardiac output is achieved best by volume-loading to a pulmonary capillary wedge pressure which is higher than the pre-operative level prior to the cross-clamp release [30].

REGIONAL CIRCULATION

The Kidney

Acute renal failure has been reported frequently following surgery involving infra-renal aortic cross-clamping. Despite improvements in patient selection, anesthetic management, and surgical techniques, a 0.2–3 percent incidence of acute renal failure following elective surgery has been reported [30]. Despite aggressive management, mortality rates approaching 25 percent may follow renal failure. Diminished pre-operative renal function, advanced age, iodinated contrast material injection, inadequate balanced salt replacement of the extracellular fluid deficit caused by angiography, mechanical bowel preparation, and fasting, may all contribute to impaired renal function following surgery. Inconclusive experimental and human studies have been published on the effects of infra-renal aortic cross-clamping on renal perfusion and intra-renal blood flow distribution. Using Xenon washout techniques to measure the distribution of intra-renal blood flow, Abbott and Austin [31] demonstrated decreased cortical blood flow during aortic cross-clamping. Gamulin et al. [32] demonstrated profound and sustained alterations in renal hemodynamics using Cr EDTA and I^{145} Hippuran clearance techniques. Despite stable cardiovascular variables, infra-renal aortic cross-clamping was associated with a 38 percent decrease in renal blood flow and a 75 percent increase in renal vascular resistance.

Microsphere renal studies have, however, demonstrated no change in the distribution of renal blood flow if adequate intravascular volume and a stable cardiac output are maintained. Failure to standardize species and study methods, cardiovascular variables, and intravenous hydration have complicated comparisons of published data [30].

Predisposing causes of acute renal failure following aortic vascular surgery include hypotension, large volumes of blood transfusion, atheromatous plaque embolization to renal arteries, intravascular myoglobin and other by-products of muscle ischemia, and supra-renal aortic cross-clamping with warm ischemic time. 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 hypovolemia develops [31]. High-dose mannitol may improve renal cortical flow, may reduce renal cell swelling following total ischemia, and, in the presence of a contracted intravascular volume, may prevent sludging of cellular debris in the renal tubules. Combinations of mannitol, dopamine, and furosemide have been advocated to prevent renal dysfunction during aortic vascular surgery [33]. Much of the data supporting the proposed benefit of these measures, however, comes from animal experiments, in which deliberate extracellular fluid expansion was not employed.

A pre-operative balanced salt solution infusion to replace extracellular fluid deficit associated with fasting, angiography, and bowel preparation, coupled with aggressive and prompt intra-operative 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.

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, Szilagryi et al. [34] reported a 0.25 percent incidence of spinal cord damage following abdominal aortic surgery, and a 0.01 percent incidence following translumbar aortography. The incidence of spinal cord damage was ten times more prevalent in ruptured, compared to 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 associated sensory loss. Spinal cord ischemia and paraplegia following thoraco-abdominal aortic aneurysm resection have been attributed variously to increased cerebrospinal fluid pressure associated with hypertension proximal to the cross-clamp, the site and duration of cross-clamp application, intra-operative hypotension, and accidental permanent interruption of critical lower intercostal and lumbar arteries. Recent conflicting experimental studies have, however, reported no relationship between spinal cord damage and arterial blood pressure, intracranial, or intraspinal pressure [35].

Intestine

In the majority of abdominal aortic aneurysm resections, 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 from the hemorrhoidal branches of the hypogastric vessels. Ischemic colitis is a well-recognized complication of abdominal aortic surgery. Prospective studies employing post-operative endoscopic examinations [36] suggest that the true

TABLE 3
Abdominal Aortic Surgery: Supplementary Intra-Operative Monitoring Techniques

Ischemia Detection
ST-segment analysis
PCWP tracing
Regional wall-motion abnormalities
Preload
Transesophageal echocardiography
Nuclear angiography
Left Ventricular Function
LVEF echocardiography
LVEF radionuclide ventriculography
LVSWI (derived)
Cardiac Output
Thermodilution
2-D echocardiography
Doppler echocardiography
Afterload
Systemic vascular resistance
End-systolic wall stress echocardiography
Tissue Oxygenation
SVO_2 fiberoptic oximetry

incidence of ischemic colitis following elective abdominal aortic surgery may be as high as 6 percent. 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 etiology of ischemic colitis.

Prophylactic measures against stress-ulceration should be employed routinely because of the established association between abdominal aortic aneurysm and peptic ulceration and the complications of gastrointestinal bleeding and peptic ulceration associated with elective resection.

INTRA-OPERATIVE ANESTHETIC MANAGEMENT

The objectives of anesthetic management include an intensive pre-operative assessment of risk factors and management of co-existing disease states; the utilization of monitoring techniques to detect signs of myocardial ischemia and impaired myocardial contractility promptly (Table 3); maintenance of adequate intravascular volume, optimal cardiac output, and tissue oxygenation; avoidance or prompt pharmacologic amelioration of untoward hemodynamic or metabolic changes associated with aortic clamping and unclamping; and intensive post-operative care.

Monitoring

Extensive monitoring of patients presenting for aortic vascular surgery is mandatory. Standard monitoring practice should include the patient's exposed extremity to check color, capillary filling, and radial pulse palpation; continuous electrocardiographic display—lead II for dysrhythmia detection and a precordial V_5 lead, modified bipolar CM_5 lead, or esophageal lead to detect S-T segment changes associated with myocardial ischemia; esophageal stethescope with thermal probe for heart/

breath sounds auscultation and temperature monitoring; pulmonary gas exchange monitoring with oximetry and capnography; neuromuscular function monitoring and bladder catheterization for urine output determination.

Preload

Pulmonary artery catheterization is indicated in the majority of patients presenting for abdominal aortic surgery to optimize intravenous fluid administration and to detect adverse hemodynamic or ischemic changes associated with aortic cross-clamping and release. Although changes in central venous pressure (CVP) predict the magnitude and direction of PCWP changes accurately in the majority of patients, there exists a group of patients in whom there is no substitute for left-sided filling pressure measurement. Because fewer hemodynamic derangements follow aortic cross-clamping in patients with aorto-occlusive disease and good collateral vascularization compared with abdominal aortic aneurysm patients, central venous pressure may closely reflect the balance among intravascular volume, venous capacitance, and left ventricular function in this patient population if no significant coronary artery disease or ventricular dysfunction is apparent [37].

Myocardial Performance

Pulmonary artery catheterization is especially indicated in patients with a history of previous myocardial infarction, angina pectoris, or signs of cardiac failure; in patients demonstrating diminished ejection fraction or abnormal ventricular wall motion on pre-operative resting or exercise radionuclide or echocardiographic studies; and in patients with evidence of redistribution on dipyridamole-thallium imaging. In addition to measurement of pulmonary artery and capillary wedge pressure (PCWP), pulmonary artery catheterization facilitates calculation of derived cardiac indices (stroke volume, cardiac index, left ventricular stroke work index), systemic and pulmonary vascular resistance, and intrapulmonary shunt. The appearance of an abnormal V-wave on the PCWP trace may indicate the onset of myocardial ischemia before surface ECG ST-segment changes occur [38].

The incorporation of intra-operative transesophageal two-dimensional echocardiography into anesthetic practice has provided a practical means of estimating left ventricular dimensions and myocardial performance in addition to the detection of wall-motion abnormalities. Measurement of end-diastolic volume and end-diastolic area allows a more precise definition of left ventricular preload, compared with central venous and pulmonary capillary wedge pressure measurements.

Myocardial Ischemia

Intra-operative myocardial ischemia may be precipitated by increases in myocardial oxygen demand caused by tachycardia, hypertension, and sympathetic responses, or by decreased myocardial oxygen supply, caused by external factors such as hypotension, tachycardia, and hypoxemia, or by internal factors such as acute coronary thrombosis and spasm [39]. Intra-operative myocardial ischemia may be detected by ECG ST-segment changes (V_5 most consistently), pulmonary capillary wedge pressure changes, and V-wave development, or segmental wall thickening changes detected by transesophageal echocardiography or cardiokymography.

Since 1985, a number of important outcome studies in patients undergoing cardiac and non-cardiac surgery have highlighted the dynamic role of intra-operative ischemia predicting perioperative cardiac morbidity [40]. Segmental wall-motion and thickening changes detected by transesophageal echocardiography may be the most sensitive indicators of ischemia, and recent preliminary data suggest that such intra-operative changes may predict patient outcome [41,42].

Anesthetic Technique

No single anesthetic agent or technique is ideal for all patients presenting for aortic vascular surgery. Controversy abounds concerning *(1)* use of regional plus general anesthesia, *(2)* use of inhalational versus opioid anesthesia, and *(3)* use of isoflurane in patients with coronary artery disease. The anesthetic agents and techniques chosen should ensure a smooth induction of anesthesia, a favorable cardiovascular dose-response relationship which preserves the delicate myocardial oxygen supply/demand balance, adequate muscle relaxation with intra-operative analgesia and amnesia. The choices of anesthetic technique include nitrous oxide/oxygen with incremental volatile agent or opiate supplementation; opiate-oxygen or an opiate-oxygen-volatile agent combination with or without regional anesthesia.

With the development of inert gas and labeled microsphere techniques for measuring coronary blood flow and metabolic indices for detecting myocardial ischemia, it is now accepted that an anesthetic technique which produces low-pressure, low-myocardial oxygen demand provides better preservation of myocardial oxygenation than a high-pressure, high-myocardial oxygen demand technique.

A combined high-dose fentanyl/oxygen/isoflurane anesthetic technique was not associated with a significantly improved left ventricular performance compared with a conventional nitrous oxide/oxygen/isoflurane/low-dose fentanyl technique. The combined opiate/oxygen/volatile agent technique, however, maintains a stable cardiac index (CI), left ventricular stroke work index (LVSWI), and systemic vascular resistance (SVR) during the cross-clamp period, and is not associated with hyperdynamic circulatory responses previously reported with the unsupplemented fentanyl/oxygen technique [43]. A combined opiate/oxygen/volatile anesthetic technique may be the technique of choice for aortic aneurysm resection in high-risk patients, since it ensures a hypodynamic circulation with preservation of myocardial oxygenation. The requirement for prolonged post-operative ventilation is, however, a major disadvantage of this technique.

Theoretically, isoflurane is the volatile anesthetic agent of choice for aortic vascular surgery. Despite its direct myocardial depressant effects, isoflurane administration is associated with preserved cardiac output due to increased heart rate and reduced systemic vascular resistance. Unfortunately, in patients with coronary artery disease, isoflurane administration may be deleterious if a vasodilatory or coronary steal effect is produced. The coronary arteriolar vasodilating properties of isoflurane are now well documented in experimental and clinical studies [44]; however, the clinical implications of isoflurane-induced coronary arteriolar dilatation in patients with coronary artery disease remain controversial.

The prophylactic or specific use of vasodilatory agents to prevent hemodynamic changes associated with surgical interventions during aortic vascular surgery remains controversial. The balance of evidence currently available would support the administration of 1–2 μg/kg/minute nitroglycerin infusion if hypertension, impaired myocardial contractility, and tissue oxygenation or signs of myocardial ischemia develop following aortic cross-clamp application [30]. This therapy should decrease arterial pressure, systemic vascular resistance, and myocardial oxygen consumption. Intravenous dobutamine infusion may also be administered to sustain myocardial function if evidence of impaired contractility develops following aortic cross-clamping.

INTRA-OPERATIVE FLUID AND BLOOD TRANSFUSION THERAPY

Patients undergoing abdominal aortic surgery usually experience major functional extracellular fluid and blood loss. Functional extracellular fluid loss into a non-functional or "third space" may follow extensive tissue trauma, manipulation, exposure, and surgical retraction. Sequestration of fluid within the lumen wall of the intestine and formation of major retroperitoneal edema account for most of the fluid shift from the circulation. The issue of whether a crystalloid or colloid intravenous fluid regime preserves circulatory homeostasis and renal function better during major vascular surgery has not been resolved. Restoration of normal intravascular and interstitial fluid volumes is a primary objective in intravenous fluid administration. Larger volumes of crystalloid solution will be required to restore the intravascular volume compared with colloid solutions. Advocates of a crystalloid regime claim greater urine output and a reduction in the incidence of oliguric renal failure following abdominal aortic surgery. Intra-operative urine output failed, however, to predict post-operative renal insufficiency in patients undergoing aortic reconstruction [45]. Conflicting data have been published, showing improved post-operative respiratory function following colloid administration [46]. A combination of balanced salt and colloid solutions, guided by appropriate central venous pressure monitoring, will ensure adequate intravascular volume, optimal cardiac output, satisfactory renal and end-organ blood flow, and minimal extravascular losses into the pulmonary interstitium and traumatized tissues.

A balanced salt solution, with or without a colloid solution, should be infused in volumes sufficient to maintain a PCWP of 10–15 mmHg during the cross-clamp period and to ensure a urine output greater than 60 ml/hour. If urine output is unsatisfactory, despite PCWP measurement of 15 mmHg or greater, diuretic therapy with mannitol or furosemide should be considered. Low-dose dopamine (2 μg/kg) following surgery has been reported to increase renal blood flow, glomerular filtration rate, urine output, and sodium excretion. The PCWP should be increased to 3–5 mmHg above the pre-operative value before cross-clamp release, to prevent hypotension and cardiac output reduction following aortic unclamping.

The techniques currently available to minimize homologous blood transfusion during elective aortic vascular surgery include multiple pre-deposit autologous collection, storage, and retransfusion; immediate pre-operative phlebotomy, hemodilution, and autologous transfusion; and intra-operative blood salvage and reinfusion. Intra-operative autotransfusion may be an economic method of reducing homologous blood transfusions significantly. Initial reports suggested a 40–50 percent avoidance of homologous blood transfusions, which has increased up to 80 percent in recent studies [47]. The initial application of autotransfusion was complicated by hemolysis and coagulation disorders; air and fat emboli, platelet and leucocyte microaggregation, and sepsis. Technological advances have virtually eliminated the significant problems of air and particulate embolization. No significant hemolysis or coagulopathies have been noted with autotransfusion techniques in recent studies. Because autotransfused blood is, in essence, a preparation of washed, packed red

TABLE 4
Abdominal Aortic Surgery: Guidelines for Anesthetic Management

1. Pre-Operative Hydration		
	Maintenance of IV fluids overnight	
2. Pre-Medication		
	Benzodiazepine ± Opiate	
3. General Anesthesia		
	Induction	Opiate: Fentanyl 50 μg/kg
		Relaxant: Non-depolarizing
	Maintenance	O_2
		Opiate: Fentanyl 20–30 μg/kg
		Volatile: Incremental enflurane/halothane
		Ventilation: Controlled normocapnia
	Nitroglycerin	Myocardial ischemia
		Hypertension >20% baseline arterial pressure
4. Intravenous Fluid Management		
	Crystalloid infusion	PCWP 10–25 mmHg
	± colloid	Urine output >60 ml/hour
	Blood	Loss >15% estimated blood volume
	Mannitol	Urine output <60 ml/hour + PCWP >15 mmHg
5. Post-Operative Management		
	Mechanical ventilation:	Cardiac and respiratory homeostasis
	Regional anesthesia:	Post-operative analgesia

blood cells suspended in saline solution without platelets and clotting factors, fresh frozen plasma and platelet concentrate transfusion may be necessary. By providing fresh warm blood with optimal pH and 2,3-DPG content, autotransfusion may prevent some of the adverse cardiovascular effects associated with extensive transfusion of stored homologous blood.

KEY POINTS FOR CLINICAL PRACTICE

Guidelines for anesthetic management of high-risk patients presenting for abdominal aortic surgery are presented in Table 4. The main drawback to this technique is the requirement for prolonged post-operative ventilation. A N_2O/O_2/low-dose opioid/volatile technique, supplemented by appropriate regional anesthesia, is an alternative worthy of consideration, especially if early post-operative extubation is contemplated.

POST-OPERATIVE MANAGEMENT: REGIONAL ANESTHESIA

Continuous epidural anesthesia has been frequently used in association with general anesthesia and, on occasion, as the primary anesthetic technique for patients undergoing aortic vascular surgery. Proponents of regional anesthesia claim reduction in volatile anesthetic and narcotic requirements and significant alleviation of post-operative pain. Elevation in skin temperature, increased graft blood flow, and reduced muscle blood flow have been observed. Combined regional and general anesthetic techniques may attenuate the increased systemic resistance with aortic cross-clamping and may produce stable cardiovascular dynamics following cross-clamp release if intravascular volume is maintained. Recent randomized prospective data from mostly major vascular surgical patients comparing general to epidural plus general anesthetic techniques noted fewer post-operative cardiovascular complications in the group receiving regional anesthesia [48].

Despite the well-known and accepted advantages of regional anesthesia alone, or in combination with general anesthesia and tracheal intubation, these techniques have not been adopted universally, partly due to the lingering controversy surrounding epidural catheters and anticoagulant therapy. The use of combined general anesthesia and continuous lumbar epidural anesthesia for major aortic vascular surgery has increased during the past decade. This technique has been associated with greater total perioperative fluid volume administration and reduced left ventricular function compared with general anesthesia alone [49]. The merits of combined regional and general anesthetic techniques, compared with conventional general anesthesia alone for aortic vascular surgery, must await the publication of more extensive clinical investigations [50].

CARDIORESPIRATORY CARE

Patients recovering from aortic vascular surgery are at risk of developing cardiac, respiratory, and renal failure in the immediate post-operative period. Close monitoring of the patient's intravascular volume status, temperature, and respiratory and renal function will be required in addition to assessment of graft patency and lower extremity blood flow. Provision of adequate analgesia is also a priority. This section will focus on the immediate post-operative ventilatory care and the influence of the site of surgical incision on respiratory function, and on the problem of hypertension in the immediate post-operative period.

Respiratory Care

The post-operative respiratory deficit is primarily restrictive with decreased functional residual capacity and pulmonary compliance. Pre-existing obstructive defects are compounded by altered secretions, impaired cough and mucociliary clearance, atelectasis, and post-operative pulmonary infections. Early post-operative intermittent mandatory ventilation is normal practice. Co-existing cardiac and respiratory disease is common in this mainly elderly patient population. The obligatory extended midline incision, abdominal distension following extracellular fluid sequestration, bed rest in the supine position, abdominal pain requiring narcotic administration, large volumes of blood and electrolyte infusion, and hypothermia following prolonged procedures may all preclude early weaning and tracheal extubation. A slow emergence from anesthesia reduces the likelihood of agitation, shivering, and cardiorespiratory instability in the early post-operative period.

The retroperitoneal approach for elective abdominal aortic aneurysm resection may be associated with significantly better perioperative oxygenation and preservation of lung volumes compared with the transabdominal approach [51]. The retroperitoneal approach may better preserve diaphragmatic contractility. The right lateral decubitus position required for the retroperitoneal approach was not associated with significant hemodynamic changes following aortic cross-clamping and release [52]. Retroperitoneal may be the preferred approach for abdominal aortic aneurysm surgery, especially in patients with impaired respiratory function [53].

Hypertension and Myocardial Ischemia

Hypertension is a common and potentially serious complication in the immediate post-operative period following abdominal aortic surgery. Postulated mechanisms include overzealous hydration during anesthesia and exaggerated replacement of blood loss; post-operative hypothermia with compensatory vasoconstriction; rebound hypertension following cessation of vasodilator therapy; pre-existing hypertension and vascular hyper-reactivity [53,54]. Recent attention has focused on the relationship between post-operative ischemic episodes and perioperative cardiac morbidity [55]. Hemodynamic stress may be precipitated by painful emergence from anesthesia, fluid shifts, temperature changes, and alterations in respiratory function. Marked changes occur in plasma cathecholamine concentrations, ventricular function, and coagulation following major vascular surgery, especially in patients with pre-existing cardiac disease [39]. Post-operative patients may have heart rate increases of 25–50 percent over intra-operative values, and post-operative ischemia typically is silent [56]. Daily clinical evaluation, serial ECGs, and cardiac enzymes should be performed to detect post-operative cardiac morbidity. Pharmacologic control of heart rate elevations and post-operative pain relief may reduce post-operative myocardial ischemia and improve patient outcome.

SUMMARY

Patients presenting for abdominal aortic surgery have a high incidence of systemic vascular disease, manifested primarily by hypertension, coronary and cerebrovascular disease, as well as co-existing respiratory, renal, and metabolic disorders. Current 30-day operative mortalities for elective abdominal aortic aneurysms vary between 1–6 percent. Patient outcome following abdominal aortic surgery depends on age, presence and extent of co-existing disease states, and the nature of the surgical procedure. Long-term outcome primarily relates to stability of any underlying disease and the extent of any ventricular dysfunction. Routine clinical assessment, resting and ambulatory electrocardiogram, chest roentgenograms, resting and exercise radionuclide ventriculography and echocardiography, and dipyridamole-thallium scanning are all designed to assess the functional status of the myocardium and to detect the presence of significant coronary artery disease. Patients with no abnormalities on routine physical evaluation and with no redistribution on dipyridamole-thallium scanning should proceed to surgery with the expectation of very low perioperative cardiac risk. Patients with evidence of coronary artery disease and significant redistribution on dipyridamole-thallium scan should undergo coronary angiography and possible myocardial revascularization before definitive aortic vascular surgery. For high cardiac-risk patients with no bypassable lesions presenting for abdominal aortic aneurysm resection, a conservative policy of serial three-monthly ultrasound or CT assessment may be adopted; selective resection should be undertaken only for rapid aneurysm expansion or symptom development. A variety of extra-anatomic and angioplastic techniques is available for similar high cardiac-risk patients with aorto-iliac occlusive disease.

The hemodynamic consequences of aortic cross-clamping, especially in aneurysm patients, include a significant reduction in stroke volume, cardiac index, and myocardial oxygen consumption with an increased systemic vascular resistence. Patients with coronary artery disease may respond to aortic cross-clamping by increasing pulmonary capillary wedge pressure and by demonstrating myocardial ischemia. Pulmonary artery catheterization is especially indicated in patients with a history of previous myocardial infarction, angina, or signs of cardiac failure, and in patients with evidence of diminished ejection fraction, abnormal ventricular wall motion, or

myocardial redistribution on pre-operative scanning. The more widespread application of intra-operative transesophageal two-dimensional echocardiography into anesthetic practice will enable measurement of left ventricular dimensions and myocardial performance and will allow early detection of myocardial ischemia. Recent outcome studies in patients undergoing cardiac and non-cardiac surgery have highlighted the dynamic role of intra-operative ischemia in predicting post-operative cardiac morbidity.

No single anesthetic agent or technique is ideal for all patients presenting for abdominal aortic surgery. A combined opiate-oxygen-volatile anesthetic agent technique will best ensure a hypodynamic circulation with preservation of myocardial oxygenation. Isoflurane should be the anesthetic agent of choice for abdominal aortic surgery, but concerns about deleterious vasodilatory or coronary steal effects have limited its use in patients with known coronary artery disease. Large-scale studies in patients undergoing cardiac surgery suggest, however, that isoflurane produces no more intra-operative ischemia than other anesthetic agents [56]. A N_2O/O_2/low-dose opioid/volatile technique supplemented by appropriate regional anesthesia may prove satisfactory, especially if early post-operative extubation is contemplated. Nitroglycerin infusion should be commenced if hypertension and signs of myocardial ischemia develop following aortic cross-clamp application. Pre-operative replacement of extracellular fluid deficits, prompt and aggressive intra-operative hydration and blood loss replacement, guided by appropriate monitoring techniques, maintenance of a stable cardiac output, and optimal surgical techniques are the best prophylactic measures to ensure adequate renal, spinal cord, and intestinal blood flow and function during the perioperative period. Adequate pre-operative antihypertensive therapy remains the most important prophylaxis against post-operative hypertension, with all its attendant risks of myocardial ischemia and infarction. The relative safety of anticoagulation following epidural catheter insertion has been established recently. The merits of a combined general and regional anesthetic technique await further detailed scrutiny.

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