# Minimally invasive cardiac surgery

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**Abstract**

**We summarise recent developments in minimally invasive cardiac surgery. We describe the modifications to anaesthetic technique, incisions, cardiopulmonary bypass and myocardial protection, and the endoscopic and robotic adjuncts that permit coronary artery surgery, valve repair and replacement, and repair of descending aortic aneurysms to be successfully carried out. The results for such surgery are summarised and compared to conventional open techniques as well as percutaneous procedures.**

**Key words:** minimally invasive, cardiac surgery.

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## Introduction

The main aim of minimally invasive surgery is decreased morbidity and mortality compared with conventional open surgery. Cardiac surgeons are primarily concerned with effective correction of surgical lesions, and reduction in operative mortality and stroke. Minimally invasive approaches are rapidly becoming part of the standard cardiac surgical repertoire thanks to patient demand and major improvements in technology and experience.

There is no formal definition of what constitutes minimally invasive cardiac surgery. The term is currently used to mean conventional cardiac operations carried out using smaller incisions and/or using alternatives to conventional cardiopulmonary bypass. A minimally invasive approach involves modifications to patient selection and standard anaesthetic technique, as well as endoscopic and robotic adjuncts to facilitate surgery. This review article outlines some of these modifications, as well as minimally invasive techniques in current use.

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## Patient selection

Although early experience in most centres has been in selected younger patients with minimal co-morbidity and good cardiac function, the patients that should eventually benefit most from a minimal access approach are elderly patients at high risk of post-operative adverse outcomes. Although patients with lung disease benefit from off-pump techniques, lung disease that might prevent prolonged single lung ventilation makes thoracoscopic and limited thoracotomy approaches difficult, as it is usually necessary to deflate one lung to facilitate access to the internal mammary artery and heart. Patients with a history or clinical examination suggestive of chronic lung disease are therefore screened pre-operatively with lung function tests. Morbid obesity makes operating through small incisions challenging: some surgeons regard it as a relative contraindication to minimally invasive approaches, although thoracoscopic surgery is not more difficult. Peripheral vascular disease is a relative contraindication to peripheral cannulation techniques for cardiopulmonary bypass.

## Anaesthesia

Minimally invasive cardiac surgery presents the cardiac anaesthetist with particular challenges. The surgical approach impinges on almost every aspect of monitoring, induction, maintenance and withdrawal of anaesthetic.

Minimally invasive thoracoscopic approaches usually require double lumen intubation and single lung ventilation, which is technically challenging. An important advantage of minimally invasive approaches is early extubation but this can only be accomplished with appropriate choice of anaesthetic agents and analgesia. This frequently includes insertion of a thoracic epidural which must be atraumatic since patients are at increased risk of complications from haematomas following intra-operative anticoagulation. Many anaesthetists are proficient in trans-oesophageal echocardiography (TOE) which is used to monitor intra-operative ventricular and valvular function, as well as endoluminal placement of intracardiac ports.

Off-pump coronary artery bypass surgery avoids many of the complications of cardiopulmonary bypass (see later in article) but it presents surgeon and anaesthetist with two major challenges, which anaesthetic and surgical technique must overcome: reduction in cardiac output when positioning the heart, and interruption to coronary blood flow during each distal anastomosis. Haemodynamic changes occur rapidly but can be anticipated by knowing the sequence of surgery, as well as by adjuncts to standard monitoring such as ST segment analysis, TOE and cardiac

**Figure 1.** Incisions used for minimally invasive cardiac surgery: upper sternotomy (aortic valve surgery), anterior thoracotomy (MIDCAB, endoACAB) and right thoracotomy (mitral valve surgery)

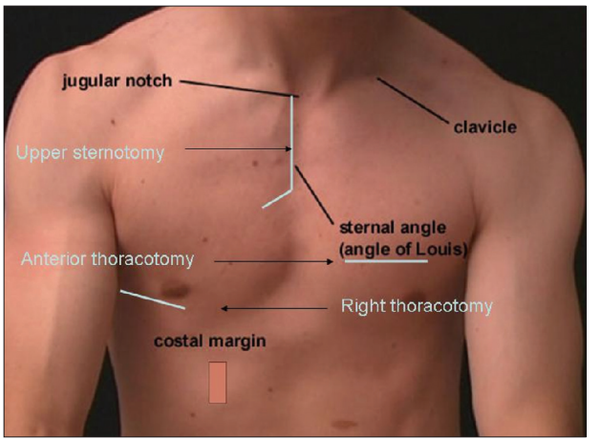



**Figure 2.** Scars from totally endoscopic coronary artery bypass surgery (TECAB)

**Figure 3.** Scar from minimally invasive mitral valve surgery

**Figure 4.** Scars from endoscopic saphenous vein and radial artery harvesting




output measurements. Inotropic support is frequently required during the distal anastomosis, during which both hyper- and hypovolaemia must be avoided. The use of TOE allows the anaesthetist to assess whether the heart is likely to tolerate particular positions, by identifying valvular regurgitation and ventricular impairment before the heart decompensates. It may be necessary to stop ventilating for short periods to optimise surgical exposure.

If patients are normothermic, not acidotic, adequately ventilating, haemodynamically stable and not bleeding once the sternum is closed, they are candidates for waking and extubation in theatre, or shortly within intensive care. Adequate analgesia is imperative to avoid agitation and hypertension which predispose to bleeding, and atelectasis which predisposes to chest infection.

## Minimally invasive incisions

Standard sternotomy and thoracotomy incisions are both associated with problematic post-operative respiratory dysfunction, immobility, wound infections and chronic pain: these complications are substantially reduced by minimally invasive approaches. Figures 1 to 4 depict some minimally invasive incisions and list the procedures that may be carried out using them.

## Disadvantages of cardiopulmonary bypass

The pathophysiological changes associated with bypass are due to more than the activation of the whole-body inflammatory response as a result of blood passing through the pump circuitry. Changes in temperature, acid-base balance, haemodilution, non-pulsatile flow, drugs, circulating volume and the mechanics

**Glossary of terms and techniques of minimally invasive CABG**

**MIDCAB (minimally invasive direct coronary artery bypass grafting)**
Left internal mammary artery (LIMA) harvesting and coronary artery anastomosis are performed, without bypass, through a small anterior thoracotomy incision

**EndoACAB (endoscopic atraumatic coronary artery bypass grafts)**
LIMA is harvested thoracoscopically, then coronary artery anastomosis is performed, without bypass, through a small anterior thoracotomy incision

**Port-access CABG (port-access coronary artery bypass grafting)**
LIMA harvesting and coronary artery anastomosis on bypass are performed through a small anterior thoracotomy; aortic occlusion and delivery of cardioplegia are endovascular

**TECAB (totally endoscopic coronary artery bypass grafting)**
LIMA harvesting and coronary artery anastomosis are performed, off bypass, thoracoscopically; the coronary artery anastomosis is usually performed with robotic assistance, and/or anastomotic aids

of bypass all contribute to dysfunction of blood constituent cascades and whole organ systems. Cardiopulmonary bypass activates five plasma protein systems (the contact system, the intrinsic and extrinsic coagulation pathways, and the complement and fibrinolytic cascade); and five cellular systems which mediate systemic inflammation (platelet, neutrophil, monocyte, lymphocyte and endothelial cell systems).

When blood encounters the non-endothelialised surfaces of the cardiopulmonary bypass circuit and the operative field, plasma proteins are instantly adsorbed onto the surface to produce a protein layer. Heparin-coated circuits change the reactivity of adsorbed proteins but do not reduce thrombogenicity. Patients are therefore aggressively heparinised (they receive 300 units of heparin per kilogram, and supplementary doses during bypass titrated against clotting studies). This is reversed using protamine at the end of the operation so that haemostasis can be achieved.

The impact of these pathophysiological processes results in multi-system dysfunction. Bleeding and thrombotic complications associated with cardiopulmonary bypass are related to activation of platelets and plasma proteins, and heparin. Bleeding times after full reversal of heparinisation do not return to normal for up to 12 hours after bypass. Disseminated intravascular coagulation (DIC) and heparin-induced thrombocytopenias (HIT) and thrombosis (HITT) are uncommon but serious complications.

Massive fluid shifts, largely into the interstitium, result from increases in systemic venous pressure, volume loading, reduction in plasma protein concentration as a result of dilution and adsorption onto the cardiopulmonary bypass circuit, and the inflammatory increase in capillary permeability described above. The combined stressors of surgery, hypothermia, cardiopulmonary bypass, and non-pulsatile flow trigger a hormonal stress response. Levels of cortisol, adrenaline and noradrenaline rise during bypass and remain raised for at least 24 hours afterwards, as does blood glucose. Circulating T3 falls below normal range. The release of numerous vasoactive substances (in addition to those described above), which act throughout organ systems, means that 'cardiopulmonary bypass turns homeostasis into physiological and biochemical chaos'.

Myocardial compliance and contractility fall because of myocardial stunning, ischaemia and oedema. Myocardial function continues to fall for six to eight hours post-operatively as a result of ischaemia-reperfusion injury, before returning to baseline. Vasodilatation and capillary leak mean that there is a progressive requirement for volume resuscitation, despite the additional volume transfused to the patient from the bypass circuit.

Pulmonary oedema is caused by activation of complement and sequestration of neutrophils in the pulmonary vasculature where they mediate an increase in capillary permeability, which is compounded by the fluid shifts described above. Cardiopulmonary bypass reduces the effect of natural surfactant, compounding pulmonary dysfunction caused by general anaesthetic and median sternotomy. Cardiopulmonary bypass increases shunts, reduces compliance and functional residual volume, and can cause acute lung injury.

Stroke is primarily due to emboli released during the cannulation and clamping of the aorta. In a small percentage of cases, stroke is haemorrhagic and attributed to the anticoagulation necessary for bypass. Haemodilution, microemboli, catecholamines, low perfusion pressure, diuretics, hypothermia, aprotinin and haemolysis all impair renal function. Peptic ulceration is a response to stress, not cardiopulmonary bypass *per se*. Pancreatitis and mild jaundice are not uncommon. Greater permeability of gut mucosa leads to endotoxin translocation, adding to the inflammatory response.

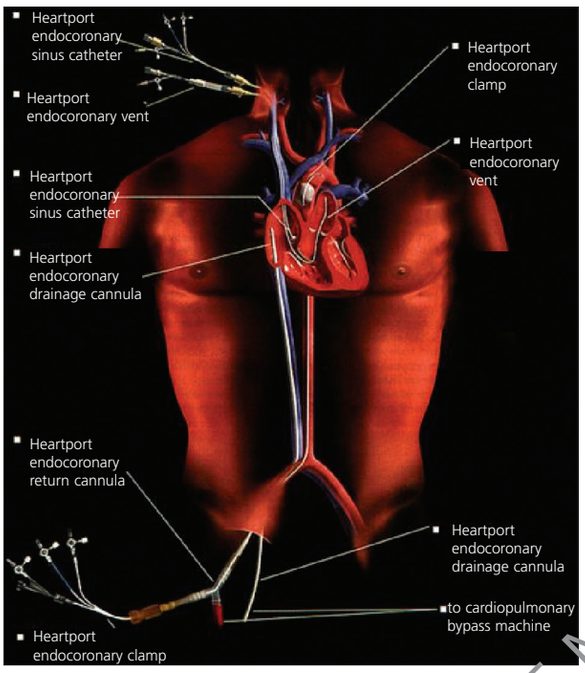
## Minimally invasive alternatives to aortocaval cardiopulmonary bypass

Three main alternatives to standard aortocaval cardiopulmonary bypass are used in minimal access cardiac surgery: off-pump surgery which aims to eliminate the pathophysiological sequelae described above, conventional cardiopulmonary bypass via peripheral cannulation and port-access bypass. Off-pump techniques are described in the section on coronary artery bypass grafting.

Femoral, subclavian and axillary approaches to cardiopulmonary bypass have been part of the standard surgical repertoire for decades. Venous drainage into the cardiopulmonary bypass circuit is through cannulae sited in the right atrium or cavae, either directly or via the femoral or internal jugular veins. Arterial return from the bypass machine can be via the femoral, subclavian or axillary arteries. In order to inject cardioplegia into the coronary ostia, the ascending aorta must be cross-clamped directly and cardioplegia instilled into the aortic root.

Port-access bypass is a modified version of femoral-femoral bypass that incorporates a method of occluding the aorta (the endoclamp) and instilling cardioplegia from a peripheral site. The heart can be arrested on bypass, enabling aortic and mitral valve surgery, as well as coronary artery bypass grafting to be carried out. As the surgeon is unable to visualise the bypass cannulae or

**Figure 5.** Port-access bypass




the cardioplegia delivery system, additional monitoring is mandatory. Radial arterial lines are sited bilaterally so that migration of the arterial cannula or cardioplegia delivery system can be detected. Fluoroscopic or transoesophageal echocardiographic guidance is used to site the cannulae. One or more ports are placed to facilitate the surgical procedure. The endoclamp consists of a triple lumen catheter with an inflatable balloon at the tip: the balloon is inflated to occlude the aorta via the first lumen, the second lumen allows aortic root pressure to be transduced and can be used as a root vent, and the third delivers cardioplegia (figure 5). It is possible to site a cannula in the coronary sinus to give retrograde cardioplegia if desired, a useful adjunct if the patient has aortic incompetence, or during long procedures. Contraindications to port-access bypass include severe peripheral vascular disease and intraluminal atherosclerosis of the aortic arch.

## Minimally invasive coronary artery bypass grafting

Off-pump surgery is limited to closed heart procedures, the most important of which is coronary artery bypass grafting. Techniques of cardiopulmonary bypass were refined in the 1960s and 1970s and the vast majority of surgeons elected to perform coronary artery surgery on-pump. The advantages of a still, clear operating field, good myocardial protection, and near complete haemodynamic and respiratory control appeared to outweigh the many disadvantages of cardiopulmonary bypass described above. Recent improvements in experience, as well as in methods of stabilising the heart without impairing cardiac function, have led to increasing numbers of institutions moving their coronary artery practice off-pump, in the expectation that patients should see a benefit from reduced rates of operative mortality and stroke, as well as other morbidity.

Conventionally performed through a median sternotomy incision, off-pump coronary artery bypass (OPCAB) may be modified so that internal mammary artery harvest and bypass grafting can be performed through a small anterior thoracotomy (minimally invasive direct coronary artery bypass [MIDCAB]), or entirely endoscopically (totally endoscopic coronary artery bypass grafting [TECAB]). Endoscopic atraumatic coronary artery bypass grafting (EndoACAB) is a half-way house where the internal mammary artery is harvested endoscopically but the coronary anastomosis is performed under direct vision. In 'hybrid' procedures, stenosed vessels suitable for percutaneous coronary intervention but beyond the limits of the surgical incision are electively stented post-operatively. Minimally invasive coronary surgery offers superior freedom from all adverse events at six months compared to isolated stenting.[1]

More than 50 randomised controlled trials of off-pump versus on-pump surgery have now been published, as well as several meta-analyses. Off-pump coronary artery bypass surgery appears to offer favourable outcomes, leading to reductions in post-operative atrial fibrillation, transfusion requirements, inotrope requirements, ventilation times, length of hospital and intensive care unit stay, and cost compared to on-pump coronary artery surgery. But no randomised trial has yet demonstrated a difference in death or stroke at 30 days or one year.

In the largest randomised controlled trial of off-pump surgery reported to date, the Prague-4 investigators randomised 400 patients with coronary artery anatomy considered amenable to both off- and on-pump revascularisation. Unlike the majority of off-pump trials, poor left ventricular function, advanced age and acute coronary syndromes were not exclusion criteria. The difference detected at 30 days in the primary end point of combined mortality, Q-wave myocardial infarction and stroke rate between the off-pump group (2.9%) and the on-pump group (4.9%) did not reach statistical significance.[2] The larger of the remaining randomised controlled trials also failed to demonstrate a difference in 30-day mortality and stroke. A significant reduction in transfusion requirements, serum markers of myocardial damage and a cost saving with off-pump surgery in low-risk patients have been shown in randomised trials.[3-5] Initial concerns that the technical demands of off-pump surgery could lead to under-revascularisation and reduced anastomotic patency have not been supported by the larger trials carried out in institutions with well established expertise in off-pump surgery.[3,4]

These findings were borne out by a large, recent meta-analysis that assessed 95 randomised controlled trials of off-pump versus on-pump coronary artery bypass grafting, of which 37 trials containing 3,369 patients were judged suitable for inclusion. No significant differences in 30-day mortality, stroke, myocardial infarction, graft patency or reintervention were demonstrated.[6]

Several retrospective analyses of large registries, on the other hand, have demonstrated a statistically significant difference in

post-operative mortality and stroke. The largest such study looked at over 11,000 off-pump and 106,000 on-pump patients operated on over a two-year period. Both groups had a similar predicted mortality but the off-pump group had lower risk-adjusted mortality (2.31% versus 2.93%, p<0.0001), lower risk-adjusted major morbidity (10.62% versus 14.15%, p<0.0001), fewer strokes (1.25% versus 1.99%, p<0.001), less renal failure post-operatively (3.85% versus 4.26%, p<0.001) and fewer rates of post-operative cardiac arrest (1.42% versus 1.74%, p<0.01).[6] Magee *et al.* reviewed 8,449 patients from two institutions (1,983 off-pump and 6,466 on-pump) operated on over a period of 30 months. Using a multivariate logistical regression analysis as well as propensity scoring, they showed that cardiopulmonary bypass was an independent risk factor for mortality (OR 1.79, 95% confidence intervals 1.24 to 2.67).[7]

Randomised prospective data comparing MIDCAB, TECAB and endoACAB to conventional off-pump coronary artery surgery are sparse. The Patency, Outcomes, Economics of Minimally invasive direct coronary artery (POEM) study compared 165 patients undergoing MIDCAB to 145 patients undergoing conventional coronary artery bypass grafting of the left internal mammary artery (LIMA) to the left anterior descending (LAD) artery. Angiographic patency was comparable, with 94.5% of anastomoses patent in the MIDCAB group compared to 96.8% in the coronary artery bypass group at six months.[8] There was no significant difference between the two groups in terms of hospital mortality or peri-operative myocardial infarction. At present MIDCAB, TECAB and endoACAB are limited to a small subgroup of patients with isolated LAD lesions unsuitable for percutaneous coronary intervention. In these patients, in experienced institutions, MIDCAB has shown to be a safe, cost-effective alternative to conventional coronary bypass surgery.[9,10] These techniques have been compared to percutaneous coronary intervention: death and stroke rates are equivalent, patency and repeat revascularisation rates are superior in the surgery groups, although percutaneous coronary intervention is more cost-effective.[1,11]

## Minimally invasive conduit harvest

The left internal mammary artery can be harvested to a variable extent through several incisions. It is important to obtain a long length (preferably the entire length) to avoid kinking or placing the LIMA to LAD anastomosis under tension. Short lengths will not reach the LAD in patients with distal disease or chronic obstructive airways disease. There are a number of specialised retractors which enable the LIMA to be harvested from first to fifth rib space via a limited thoracotomy. Thorascopic internal mammary artery (IMA) takedown is an alternative method of harvesting the IMA which has several advantages. Firstly, rib resection and retraction are avoided. Secondly, the entire length of the IMA can be mobilised, avoiding kinking, tension on the anastomosis and IMA steal syndromes resulting from failure to ligate proximal intercostals branches. The disadvantages are few. Harvest takes a little longer, with a longer learning curve. Insufflation of carbon dioxide to improve visibility may result in haemodynamic compromise; uncontrollable haemorrhage may mandate median sternotomy. Endoscopic harvest has been shown to lead to a reduction in pain without adverse effects on conduit patency.[12]

Minimally invasive saphenous vein harvest confers particular benefits. In addition to significant post-operative pain and decreased mobility, the standard method of harvesting the saphenous vein through a long, continuous incision often results in delayed wound healing due to cellulitus, oedema, large skin flaps, fat necrosis, haematoma and sympathetic dystrophy. There are several systems for minimal access harvest. In skilled hands, all of them result in comparable quality conduit. An alternative is using a 'stripper' which allows vein to be harvested through multiple small stab incisions without a camera. Two meta-analyses comparing minimally invasive with conventional methods of saphenous vein harvest have shown significant reduction in the rates of wound infection,[13] in non-infective leg wound complications and length of hospital stay.[14] There is little evidence to suggest that endoscopic harvesting has an adverse effect on the quality of conduit.



## Minimal access valve surgery

Minimal access mitral valve surgery via a limited right thoracotomy has been successfully performed with various modifications in hundreds of patients to date.

Access to the mitral valve normally requires selective cannulation of each cava, which can be achieved via a combination of femoral or port-access cannulation of the inferior vena cava and direct superior vena caval cannulation through the thoracotomy incision, or via the internal jugular vein. Mean arterial pressure is monitored via bilateral radial arterial lines. Surgery may be safely carried out on the beating or fibrillating heart, avoiding the need to occlude the aorta and administer cardioplegia. Transoesophageal echocardiography is necessary to assess removal of air from the heart and valve function prior to weaning bypass.

The aortic valve is accessed through an upper sternotomy incision. The technique is a modified version of the standard open technique, although port-access bypass can be used instead of aorto-caval bypass. Retrograde cardioplegia is used if desired and the heart is vented via the right superior pulmonary vein, or via the dome of the left atrium. The main modification is that the operating surgeon obtains the best view of the aortic valve standing over the patient's right shoulder. Removal of air from the heart is carried out under echocardiographic guidance in the standard fashion, elevating the apex of the heart to facilitate this using internal defibrillator paddles.

While several small, single-centre studies have claimed equivalence in terms of surgical outcome at up to three years follow-up and reduction in length of hospital stay in the minimally invasive surgical groups, there are no randomised controlled trials of minimally invasive valve surgery versus conventional valve surgery.[15,16]

## Thoraco-abdominal aortic aneurysm repair

Thoraco-abdominal aortic aneurysm repair is associated with a mortality of 10–20% and a risk of paraplegia of approximately

### Key messages

- Minimally invasive coronary artery bypass grafting (CABG), mitral and aortic valve surgery are all technically possible
- Evidence of equivalence in surgical outcome, stroke and mortality as well as the expected improvements in post-operative morbidity is limited to relatively small, non-randomised series at experienced institutions
- Off-pump CABG has a growing body of high-quality evidence that supports its superiority over on-pump CABG

10% despite refinements in surgical technique and spinal cord protection. Large thoraco-abdominal incisions are associated with considerable morbidity. Endovascular stenting has established itself as the treatment of choice in selected disease limited to the descending thoracic aorta, as it is associated with a lower risk of mortality and paraplegia. Combined endovascular and surgical repair of thoraco-abdominal aortic aneurysms is a particularly recent and exciting development. The abdominal aneurysm is repaired surgically, which allows reimplantation of visceral vessels and also provides access for endoluminal stenting. Excellent results[17] have meant that at experienced institutions thoraco-abdominal surgery is no longer the preserve of the cardiothoracic surgeon.


## Summary

Minimally invasive approaches to most aspects of adult cardiac surgery are technically feasible. Evidence of equivalence in surgical outcome, stroke and mortality as well as the expected improvements in post-operative morbidity, length of hospital stay and quality of life following discharge, is currently limited to relatively small, non-randomised series at experienced institutions. Large multi-centre randomised trials of minimally invasive versus conventional approaches are required. Off-pump coronary artery surgery is the single exception to this statement: a growing body of high-quality evidence demonstrates equivalent or superior outcomes with off-pump versus on-pump surgery.


## Conflict of interest

None declared.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