Anesthesiology

A Practical Approach

Basavana G. Goudra
Michael Duggan
Vidya Chidambaran
Hari Prasad Krovvidi Venkata
Elizabeth Duggan
Mark Powell
Preet Mohinder Singh *Editors*

Springer

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Foreword

There are an increasing number of textbooks published over the last several decades in the field of anesthesiology. Each of them has attempted to fill a particular niche. *Anesthesiology: A Practical Approach* fills the niche of practical textbooks which help the reader in providing daily care to their patients. It is also geared to provide a pragmatic approach to patient care that helps train the reader as a consultant anesthesiologist and is therefore an excellent resource to prepare for oral examinations. Dr. Goudra, a clinical associate professor of anesthesiology and critical care at the Perelman School of Medicine at the University of Pennsylvania, has been a prolific academic and has already published several textbooks. He has assembled an international group of section editors and authors to ensure a broad perspective of best practices from the preoperative through postoperative care. The readers of this text will clearly be enlightened and prepared to care for patients on a daily basis and demonstrate proficiency on any oral examinations.

Philadelphia, PA, USA   Lee A. Fleisher

Preface

By virtue of being the cornerstone of medical practice, the specialty of anesthesiology continues to expand into areas few ever thought possible. As anesthesia providers, we evolve at a faster rate than any other specialty, especially when presented with new and more complex challenges. Surgeons continue to test our versatility and adaptability, but the demands posed by nonsurgical specialties continue to grow at an ever-increasing pace. In fact, in many major university teaching hospitals, including the Hospital of the University of Pennsylvania, the number of procedures performed outside the operating rooms exceeds traditional surgeries. Whereas there is a decline in surgeries like lung resections, there has been an increase in procedures performed in interventional bronchoscopy suites. While the face of gastrointestinal surgery has changed, endoscopic procedures continue to grow at an astronomical pace. The neuroradiologists and cardiologists continue to displace the surgeons and defy the anesthesia providers.

There is no dearth of good textbooks in the field of anesthesiology. In fact, subspecialty books abound including my own, *Out of Operating Room Anesthesia*. Though online availability of books/chapters has revolutionized the way we access information, there is still a need for a book that is subspecialty-focused. More specifically, the need for a book that incorporates anesthesia management of various surgical and medical procedures under one roof has been long awaited.

The current book, *Anesthesiology: A Practical Approach*, is designed to be useful for both the everyday anesthesia practitioner and the resident preparing for their exam. The book is divided into seven sections: The first six sections address specific procedures pertaining to cardiothoracic surgeries, out of operating room procedures, pediatric including neonatal and fetal surgeries, and obstetrics, vascular, and neurosurgeries. The last section deals with many surgeries that either cross into multiple specialties or are entirely unique.

Each chapter has information that will assist the anesthesia provider to tailor the anesthetic to the specific procedure. We attempt to summarize and present information in the form of tables whenever possible, so that residents or postgraduate students can efficiently extract information when preparing for exams. We also attempt to be as thorough as possible, so that the 83 chapters discuss almost every situation that could be tested. Every chapter can also be read in isolation.

I thank my section editors from the USA, the Great Britain, and India for shouldering this mammoth task. Michael Duggan, MD, and Elizabeth Duggan, MD, from Emory University Hospital have contributed and edited the sections on cardiothoracic and vascular anesthesia, respectively. The section on neuroanesthesia is edited by Hari Krovvidi, FRCA, from the Birmingham University Hospital, UK. Vidya Chidambaran, MD, from the Cincinnati Children's Hospital has edited the challenging section of pediatric anesthesia. Mark Powell, MD, from the University of Alabama at Birmingham, Birmingham, Alabama, provided his valuable input into the obstetric anesthesia section. Finally, I would like to thank Preet Mohinder Singh, MD, from AIIMS, India, for his assistance with the section "Out of Operating Room Anesthesia."

I am extremely grateful to the contributors from across the world. The invaluable insight and unique expertise brought by each contributor made this project possible. I also thank Joanna Renwick, editor of the clinical medicine section, and Abha Krishnan, project coordinator (Books) of Springer Nature, for their unrelenting support in ensuring the timely production of the book.

Finally, I would like to thank Lee A. Fleisher, MD, the Robert D. Dripps professor and chair of anesthesiology and critical care and professor of medicine at the University of Pennsylvania and the champion of evidence-based anesthesia, for his continued support.

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Part III Pediatric Anesthesia

About the Editors

Basavana G. Goudra, M.D., F.R.C.A., F.C.A.R.C.S.I. the principal editor of the book *Anesthesiology: A Practical Approach*, is a clinical associate professor of anesthesiology and critical care medicine at the Hospital of the University of Pennsylvania, Philadelphia, USA. He is an internationally recognized expert in the area of out of operating room anesthesia, specifically in the field of gastrointestinal endoscopy. Dr. Goudra graduated from Bangalore Medical College, Bangalore, India, and completed his residency at the Jawaharlal Nehru Institute of Medical Education and Research, Pondicherry, India. After further training in the Republic of Ireland and Cincinnati Children's Hospital, Cincinnati, USA, he was appointed as a consultant anesthetist at the Russells Hall Hospital, UK. In 2008, he was appointed as a member of the faculty in the Hospital of the University of Pennsylvania. He has over 60 PubMed-indexed publications that include scientific papers, case reports, meta-analysis, reviews, and editorials on a wide range of anesthesia- and pain-related topics. He lectures at the American Society of Anesthesiology annual meetings on a regular basis. He has invented airway devices including the "Goudra Bite Block" and "Goudra Mask Airway," which will improve the safety of upper gastrointestinal endoscopy in the years to come. He is also working on a number of other projects in the area of graduate medical student and resident education. The book *Out of Operating Room Anesthesia: A Comprehensive Review*, edited by Dr. Goudra, has been acclaimed by reviewers and is popularly used in the field.

Michael Duggan, M.D., F.A.S.E. is an assistant professor at Emory University Department of Anesthesiology, where he is the director of cardiothoracic anesthesiology and perioperative echocardiography. He gained his Primary ABA Certification in Anesthesiology and NBE Advanced Perioperative TEE Certification in 2011. He had previously completed an internship in internal medicine at Virginia Commonwealth University Health System and a residency and fellowship at the University of Pennsylvania Health System. He then became clinical assistant professor at Thomas Jefferson University Department of Anesthesiology prior to his appointment at Emory University.

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Hari Prasad Krovvidi Venkata, M.B.B.S., M.D., F.R.C.A. gained his medical degree from Gandhi Medical College, Hyderabad, India, in 1996 and his MD in anesthesia from the Postgraduate Institute of Medical Education and Research, Chandigarh, India, in 1999. He completed various senior house office roles in India and the UK, before becoming a specialist registrar at Birmingham School of Anaesthesia, UK, where he is now a consultant in neuroanesthesia.

Elizabeth Duggan, M.D. is an assistant professor at Emory University School of Medicine in Atlanta, Georgia. She completed her internship at Duke University Medical Center and residency training at the University of Pennsylvania. Additionally, she spent an additional postgraduate training year as a liver transplant fellow at the University of Pennsylvania. Dr. Duggan joined the faculty of Thomas Jefferson University as the director of hepatobiliary anesthesia and later transitioned to Emory SOM. While on staff at Emory University Hospital, she has held the roles of director of vascular anesthesia and medical director of the PACU and, most recently, has been appointed the chief of service for the general, vascular, neuroanesthesia, and kidney/liver transplant service. Her primary clinical roles are as a member of the liver transplant and vascular teams; her research focus lies within perioperative outcomes specifically in obstructive sleep apnea and stress hyperglycemia.

Mark Powell, M.D. gained his medical degree from the University of Alabama at Birmingham in 2008, where he also completed his internal medicine internship, anesthesiology residency, and obstetric anesthesiology fellowship. He gained his American Board of Anesthesiology certification in 2013. He is now an assistant professor at this institution and program director of the Obstetric Anesthesiology Fellowship.

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Part I

Cardiothoracic Anesthesia

1 Anesthesia for Coronary Artery Bypass Grafting with and Without Cardiopulmonary Bypass

Michael A. Evans and Mark Caridi-Scheible

CABG and OPCAB patients have very similar demographics. The average patient is 66 years old, male, and Caucasian. Approximately 45–50% of patients present electively for surgery with both approaches. In-hospital mortality does not appreciably differ between CABG and OPCAB, at 3.0% and 3.2% respectively. OPCAB may be associated with a minor but statistically significant increase in hospital days (0.6 of a day) and overall cost ($1497) [1].

Indications for Surgery Versus Percutaneous Coronary Intervention (PCI)

There has been substantial research regarding the selection of appropriate candidates for surgical revascularization in the presence of coronary artery disease (CAD). Table 1.1 is dedicated to the clinical trials comparing outcomes in PCI versus CABG. In multi-vessel disease, CABG and OPCAB often provide superior outcomes to PCI. In low-complexity lesions, PCI is often non-inferior to CABG. Overall, in comparison to PCI, CABG and OPCAB show a decreased need for repeat revascularization procedures but often have a higher rate of cerebrovascular accidents (CVA).

Preoperative Risk Reduction

The cardiac surgical population has been one in which preoperative "preconditioning" has been shown to decrease morbidity and mortality. A 2012 Cochrane review showed that preoperative physical therapy decreased postoperative pulmonary complications in elective cardiac surgery [6]. Cessation of tobacco use four or more weeks prior to cardiothoracic surgery is likely to reduce complications [7]. In elective cases, a multidisciplinary approach involving a patient's cardiologist, cardiothoracic surgeon, and anesthesiologist must include preoperative optimization that comprehensively evaluates and identifies predictors of intra- and postoperative complications and seeks to correct them. In addition to a standard pre-anesthetic evaluation (history, physical, interpretation of existing diagnostic testing), bypass surgery patients require an evaluation specifically focusing on: myocardial ischemia and the potential for revascularization, ventricular function with notable regional wall motion abnormalities and the carotid arteries for atherosclerotic burden. In non-elective surgeries, such as in patients with recent myocardial infarction who remained hemodynamically stable, other factors such as systemic heparinization

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Table 1.1 Selection of ideal candidates for operative revascularization: CABG/OPCAB versus PCI

Name of trial	Year	Study design	Summary
SYNTAX [2]	2009	1800 patients with 3-vessel or left main CAD. Randomized to PCI or CABG. Multicenter, parallel-group, randomized, controlled trial	Major cardiovascular events more frequent in PCI arm. Main contributor was need for repeat procedure for revascularization in PCI patients. CABG patients had more CVAs. Data suggested PCI and CABG were equivalent in low-complexity lesions
FREEDOM [3]	2012	1900 patients with diabetes mellitus and angiographically-confirmed multi-vessel CAD. Open-label, multicenter, randomized controlled trial	Among the study population, CABG decreases death rate and rate of myocardial infarction when compared to PCI. Increased rate of CVA in the CABG arm
BEST [4]	2015	880 patients with multi-vessel CAD. Randomized to PCI with second generation DES or CABG. Prospective, open-label, randomized controlled trial	PCI with drug-eluting stents (second generation) instead of CABG in the study population yielded 4.7% absolute increase in death, myocardial infarction (MI), or need for revascularization at study endpoint
EXCEL [5]	2016	1905 patients with left main CAD. Randomized to PCI with second generation DES or CABG. Multicenter, open-label, randomized controlled trial	PCI found to be non-inferior at 3 years with regard to death, myocardial infarction, and stroke

tion and antiplatelet therapy must be examined. These patients have a higher risk of surgical complications, some of which depend on timing of surgery. In patients that have surgery within three days of ST-elevation myocardial infarction (STEMI), there is a 33% reoperation rate, whereas when surgical revascularization occurs after three days, the reoperation rate is 3% [8]. In emergent cases, such as patients with cardiogenic shock after STEMI that have surgery within 6 h of presentation, in-hospital mortality has been shown to be 10.8%. Female sex, preoperative cardiogenic shock, preoperative troponin-I level, and timing of surgery have all been shown to predict morbidity and mortality in this population [9]. Performing an emergent procedure is indicated in active non-correctable ischemia, cardiogenic shock, failure or complication of PCI, and mechanical complications of ischemia such as left ventricular rupture and acute mitral regurgitation.

Principles of Management

The dominant management principle for these patients rests with the fact that they are in need of revascularization and as such, strategies to increase oxygen supply and decrease demand are of paramount importance. Standard induction strategies are modified, and pre-induction monitors differ from patients that do not possess inducible ischemia. Maintenance of consistent perfusion pressure is critical to ensuring oxygen supply to susceptible myocardium. Avoidance of tachycardia allows the anesthesiologist to minimize cardiac demand, and proper depth of anesthesia and analgesia prior to airway instrumentation helps to avoid demand ischemia.

Monitoring

All cardiac surgery is performed utilizing standard American Society of Anesthesiologists (ASA) monitors. Additionally, invasive arterial and central venous access are required, along with a central and peripheral site for temperature monitors, and a catheter to drain the bladder. Often, processed electroencephalography is utilized, and select patients may benefit from cerebral oximetry (near-infrared spectroscopy, NIRS) if concern for intraoperative cerebral hypoperfusion may arise. Point-of-care blood testing is also required, which allows the anesthesiologist and perfusionist to obtain both serial activated clotting times (ACTs) and arterial blood gas analysis. In select patients, transesophageal echocardiography (TEE) and/or a pulmonary artery catheter will be utilized for additional monitoring.

Coronary artery bypass surgeries necessitate these invasive monitors because critical coronary artery disease can lead to myocardial ischemia and beat-to-beat hemodynamic monitoring allows for the ability to rapidly correct any perfusion deficits. Surgical re-vascularization also involves manipulations of the heart and great vessels that lead to drastic changes in hemodynamics which may not be experienced in other procedures.

An intra-arterial catheter is typically placed prior to the induction of anesthesia. The radial artery is commonly chosen for cannulation for several reasons: a dual blood supply to the hand also includes the ulnar artery, and the course of the radial artery is relatively straight and superficial leading to a relative ease of insertion. Communication with the surgical team is paramount prior to placing a radial arterial line, as the radial artery is often utilized as a vascular conduit in coronary artery bypass surgery.

The type of central venous catheter used in these surgeries varies, but placing an introducer sheath will allow for the optional placement of a pulmonary artery catheter (PAC) into the same vein if deemed appropriate. If a pulmonary artery catheter is not needed, a separate infusion catheter may be placed through the sheath. It is often acceptable to place a central venous line after induction of anesthesia, unless a patient would be more safely anesthetized with central access in place. Patients with poor peripheral access may qualify for a pre-induction central line, along with patients in cardiogenic shock or exhibiting preoperative hemodynamic instability.

There is no clear method in choosing which patients might benefit from placement of a pulmonary artery catheter. A recent retrospective observational study of patients receiving primary CABG at a single center showed no harm nor benefit in managing CABG patients with a PAC when undergoing a primary CABG [10]. However, it did show that utilization of a PAC added significant cost to the patient's hospitalization. Randomized controlled trials in high risk surgical patients have repeatedly shown no benefit to ICU management directed by PACs, but these studies were not exclusive to cardiac surgical patients [11, 12]. Many anesthesiologists choose to utilize a PAC in patients with a reduced ejection fraction or valvular heart disease though supporting data for this approach is lacking.

The ASA and the Society of Cardiovascular Anesthesiologists (SCA) recommend utilization of transesophageal echocardiography (TEE) in all open-heart and thoracic aortic surgical procedures, and suggests that TEE be considered for all coronary artery bypass graft surgeries [13]. Additionally, the American College of Cardiology supports this recommendation, as CABG is a class IIa indication for TEE monitoring [14].

Oxygen Supply and Demand

Table 1.2 includes a summary of modifiable hemodynamic aspects that contribute to optimization of oxygen delivery and minimization of demand.

Based on the variables listed in Table 1.2, several conclusions can be made. Tachycardia is perhaps the most detrimental hemodynamic parameter that can be modified by the anesthesiologist, as it both decreases oxygen supply and increases oxygen demand. Within a standard range, cardiac output depends linearly on heart rate such that severe bradycardia is harmful as it sacrifices oxygen delivery. A slow to normal heart rate is therefore optimal. Normotension is

Table 1.2 Modifiable aspects in myocardial ischemia

Hemodynamic variables that decrease myocardial oxygen demand	Hemodynamic variables that increase myocardial oxygen supply
Decreased heart rate	Decreased heart rate
Decreased contractility	Increased coronary blood flow [multifactorial]
Decreased afterload/ decreased LV wall stress in systole [multifactorial]	Increased CaO_2 [increase in Hgb & SaO_2]

also desired, as diastolic blood pressure strongly influences coronary perfusion pressure along with left ventricular end-diastolic pressure. Supra-normal blood pressure often cause harm because increases in afterload and systolic blood pressure contribute to left ventricular wall stress and subsequently increase oxygen demand in the myocardial tissue at risk.

Coronary Artery Bypass Grafting Utilizing Cardiopulmonary Bypass (CABG)

Historically, the first successful utilization of cardiopulmonary bypass for surgery in humans was in 1953 when surgeon John Gibbon closed an atrial septal defect [15]. The techniques and technology have evolved greatly since that time, and CPB has been utilized for a plethora of cardiac and noncardiac surgeries. CPB is typically performed via midline sternotomy, but peripheral or alternative cannulation is possible in the presence of complicating anatomic factors.

Preoperative Anesthetic Management

For elective CABG patients, special care should be taken to perform a physical exam on the day of surgery, as patients' comorbid conditions should be optimized for their procedure. Some anesthesiologists may prefer placement of central access preoperatively depending on patient factors and institutional preference. All patients generally will receive a preoperative arterial line and large-bore intravenous access. All patients should be screened for contraindications to TEE placement, even if intraoperative TEE is not initially planned. Lastly, expectations regarding postoperative management, such as extubation occurring in the operating room or the ICU, should be discussed with the patient and their family if applicable. Patients requiring heparin or nitroglycerin infusions for active or dynamic myocardial ischemia should not have these infusions stopped prior to induction.

Induction and Maintenance of Anesthesia

There are several approaches to safe induction of anesthesia in patients with known coronary artery disease. Historically, an opioid-heavy induction technique was utilized, as opioids alone don't routinely depress myocardial function and blood pressure is usually preserved. Opioids also blunt the sympathetic response to laryngoscopy and intubation of the trachea. If opioids are chosen as the primary induction agent, a second agent that contains amnestic properties must also be administered to reduce the chance of recall. However, current trends for rapid post-operative emergence and neurologic evaluation, along with known complications of rapid high-dose opioid administration (chest wall rigidity and bradycardia), make the classic opioid-dominant method less common.

A multimodal approach to induction is typically utilized including judicious use of propofol, etomidate, or ketamine combined with a moderate dose of opioid and lidocaine. Throughout the perioperative period and specifically during induction, titration of a vasoactive agent such as phenylephrine or norepinephrine helps ensure appropriate coronary perfusion pressures. A beta-blocking agent such as esmolol should also be readily available to control the critical variable of heart rate, as discussed earlier. Neuromuscular blockade is typically utilized to facilitate tracheal intubation.

Typically, anesthesia is maintained with a volatile inhalational anesthetic although there is no absolute contraindication to total intravenous anesthetic (TIVA) if preferred. There is some data to suggest that volatile anesthetics may be cardio-protective [16], however the TIVA styles in the meta-analysis were variable and it appears that propofol-based TIVA may be protective as well [17]. Surgical stimulation varies tremendously throughout the procedure, and depth of anesthesia along with anticipatory analgesia must be titrated continuously prior to cardiopulmonary bypass. A baseline TEE evaluating regional myocardial performance, volume status, valvular heart disease, presence of intracardiac shunts and atherosclerotic disease of the aorta is performed prior to initiation of CPB.

Intraoperative Anesthetic Management: Pre-bypass Period

Because of the length of surgery, hypothermia, and non-pulsatile flow, cardiac surgery patients may be at increased risk of nerve and other positioning injuries. Extreme care should be taken to pad and position a patient appropriately prior to skin preparation and draping by the surgical team, as the anesthesiologist will have limited access to extremities with the patient in the supine position with arms tucked at their sides. This includes the lower extremities which are often prepped and draped for saphenous vein harvest.

The most important goal for an anesthesiologist in the pre-bypass period is to prevent and treat myocardial ischemia. The tools utilized for ischemia monitoring include continuous electrocardiogram, transesophageal echocardiogram, and surveillance of changes in central pressures via transduction of a central venous line or PAC. ST-segment changes in the electrocardiogram is a non-invasive and easily-visualized monitor for new-onset cardiac ischemia. Intraoperative TEE monitoring is a valid diagnostic tool for ischemia associated with left ventricular systolic dysfunction or regional wall motion abnormalities (RMWAs). Lastly, abrupt increases in central venous or pulmonary artery pressures may signify that ischemia is affecting systolic or diastolic performance.

Fluid restriction prior to CPB is a key concern. Prior to initiation of CPB, the circuit requires a priming volume which will dilute the patient's hematocrit. Thus, further hemodilution of a patient's circulating red cell mass before initiation may drive the hematocrit lower than desired. As mentioned earlier, oxygen content is of critical importance in these patients with myocardium at ischemic risk. If the patient's hematocrit is sufficiently low preoperatively, several units of blood may need to be added to the bypass circuit priming solution. Hydroxyethyl starch and other non-albumin colloids should be avoided, as they have been shown to increase blood loss, postoperative acute kidney injury (AKI), reoperation due to bleeding, and blood product transfusion requirements [18, 19].

Surgical Principles

Prior to cardiopulmonary bypass, the surgical team must perform sternotomy, expose the heart and harvest any arterial and venous conduits required to bypass diseased coronary vessels. Sternotomy provides direct access to the heart and great vessels, facilitating cannulation and access to the internal mammary artery (IMA) if it is to be utilized. Close communication with the surgical team during this time is essential as the anesthesiologist may be required to pause ventilation and temporarily deflate the lungs in order to avoid inadvertent lung injury. During takedown of the IMA, surgical exposure may be ameliorated by decreasing the patient's tidal volumes and reducing positive end expiratory pressure (PEEP). Small doses of heparin (typically 5000 units) are generally administered during harvest to prevent fibrin deposition in the bypass conduits. Some surgeons may prefer to avoid any heparinization during sternotomy in order to minimize blood loss and prevent excessive bleeding from complicating their exposure.

Initiation of Cardiopulmonary Bypass

Before going on CPB, cannulae must be inserted by the surgeon to drain venous blood to the pump and reinfuse it into the arterial system. To prevent coagulation of blood within the cannulae, bypass machine and oxygenator (a catastrophic event), the patient must be systemically anticoagulated. Typically, 300–400 units of heparin per kilogram of body weight is bolused after dissection and exposure of the heart is completed. Argatroban or bivalirudin are alternative agents in the case of heparin allergies. Point of care (POC) activated clotting time (ACT) is generally used to monitor and re-dose anticoagulation. Goal ACT may vary by institution, however greater than 400 s is a common goal. Initiation of an antifibrinolytic infusion such as of tranexamic acid (TXA) or aminocaproic acid is currently recommended [20, 21]. Heparin resistance should be suspected if goal ACT is not achieved and administration of antithrombin III should be considered [22].

Traditionally, an aortic cannula is placed into the ascending aorta proximal to the innominate artery and distal to the planned location of the aortic cross-clamp (Fig. 1.1). In order to avoid unintended aortic dissection or intramural hematoma (IMH), the blood pressure is lowered via pharmacologic means or positioning (reverse Trendelenburg) prior to aortic cannulation. After the cannula is secured, the perfusionist will test the arterial flow to ensure proper line pressure and verify placement. Following a successful line test the arterial pressures can be normalized. Venous cannulation typically proceeds with atriotomy via the right atrium and insertion of the venous cannula into the inferior vena cava (IVC). Retrograde autologous priming (RAP) then commences, which consists of permissive backbleeding into the CPB circuit to reduce the amount of fluid needed to prime the circuit. This drainage rapidly decreases intravascular volume, so positioning manipulations (Trendelenburg) or temporary pharmacologic support with pressors may be indicated at this time. The pump is then activated and the flow is gradually increased until acceptable output is achieved (typically a cardiac index >2.2 L/min/m^2). Maintenance of anesthesia is generally achieved by a vaporizer attached to the oxygenator of the bypass circuit, so it is important to confirm with the perfusionist that their vaporizer is delivering the desired amount of anesthetic. The anesthesiologist will stop the ventilator and turn off their own vaporizer once the full transition of flow from the bypass machine is confirmed by the perfusionist.

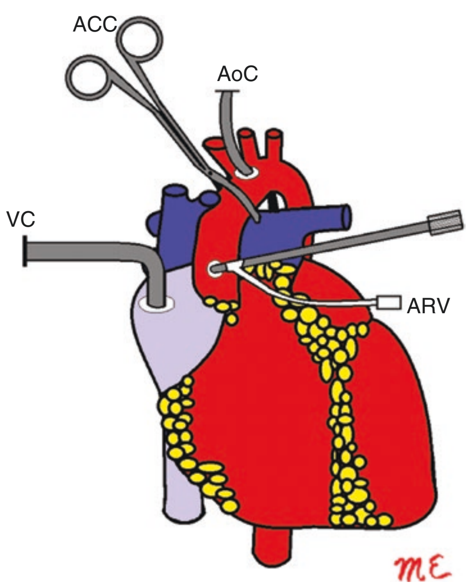

Fig. 1.1 Cardiac instrumentation. *ACC* aortic cross clamp, *AoC* aortic cannula, *ANT* antegrade cardioplegia cannula, *ARV* aortic root vent, *VC* venous cannula

Several other steps take place after achieving full flow on CPB. A means of cardioplegia administration must be provided, most commonly via an antegrade cannula placed in the aortic root. However, as delivery of antegrade cardioplegia relies on some forward patency of the coronaries, in some cases the surgeon may also choose to place a retrograde catheter into the coronary sinus to deliver cardioplegia through the coronary venous system. Next, the mean arterial pressure is lowered and the aorta is cross-clamped by the surgeon. Immediately following placement of the cross-clamp, cardioplegia is given to arrest the heart. An empty heart with complete and rapid cardiac arrest is crucial to ensure optimal myocardial protection.

The basic steps of the operation proceed in the following order:

- Patient is cooled to a target temperature (typically 32–34 °C)
- Diseased coronaries are opened distal to the blockages
- Grafts are sewn to target coronary vessels ("distal anastomoses")
- Patient Rewarmed
- Aorta Unclamped
- Partial Clamp Applied to Ascending Aorta
- Free end of grafts sewn to proximal aorta ("proximal anastomoses")
- De-airing of Ascending Aorta and Grafts
- Partial Clamp Removed
- Weaning of CPB

On-Pump Anesthetic Management

While on pump, the perfusionist is generally managing acute changes in hemodynamics by manipulating pump flows and bolusing vasopressors directly into the circuit. Variability in blood pressure is to be expected as a result of requested pump flow alterations and delivery of cardioplegia which is often vasodilatory. It should be noted that despite improvements in circuit materials and pump technology, the bypass machine can induce a significant inflammatory response in the patient that results in persistent vasoplegia. For these less acute hemodynamic changes, the anesthesiologist may be required to titrate background infusions of vasopressors. The anesthesiologist must continue to monitor the patient carefully and maintain good communication with the perfusionist and surgeon to manage these issues. Hyperglycemia is often induced as part of the inflammatory response and should be managed via an insulin infusion. Preparation for the separation from bypass, including the setup of inotropic infusions and the future need for hemostatic blood products, should be accomplished during this period. As the bypass circuit and cell-conservation systems consume platelets and plasma-circulating factors, these factors should be considered in the assessment for necessary hemostatic blood products post-bypass. Algorithms for this are highly institution and patient-population dependent and beyond the scope of this chapter. Management of anticoagulation is generally done by the perfusionist, but the anesthesiologist should remain aware of the total dose of heparin administered.

Separation from CPB

Prior to separating from bypass, the heart must be adequately recovered and prepared to resume full circulatory support for the body. The criteria for this are that the patient be completely rewarmed, that the heart has resumed normal rate and rhythm and that adequate time (generally at least 10 min) has elapsed since release of the cross-clamp for adequate coronary reperfusion. Drugs such as lidocaine and esmolol are typically given by the perfusionist before release of the clamp to prevent malignant arrhythmias, but sometimes defibrillation is required. Despite adequate reperfusion time, significant myocardial stunning may still be present either from residual cardioplegia or prior ischemia. This stunning can be overcome with use of inotropic agents, the selection of which include norepinephrine, dobutamine, epinephrine or milrinone. Epicardial pacing should also be considered if the heart is unable to achieve acceptable rate.

Once criteria are met, separation from bypass can begin. Depending on institution, this may be directed by the anesthesiologist or the surgeon, but in all scenarios clear communication amongst perfusion, surgery and anesthesia is critical for success. The process of weaning from CPB involves slowly impeding venous drainage to allow pre-load to return to the heart while slowly reducing pump flows. The heart's tolerance of this process should be monitored by direct visualization, by TEE when possible and by close observation of filling pressures on central line or PAC. For a closed-chamber procedure such as coronary bypass, residual air in the heart is not typically expected so excessive de-airing maneuvers are not required unless air is visualized on TEE. Once it is clear the heart is tolerating minimal circulatory support, the pump flow is stopped completely. The venous cannula is typically removed first and any residual blood volume left in the pump reservoir is slowly reinfused via the arterial cannula. The blood pressure is then lowered to a systolic pressure of 90–100 mmHg and the aortic cannula is removed. Heparin reversal with protamine is accomplished, the dosing for which is also institution dependent but is based on total heparin administered and should achieve ACT level close to baseline. Slow administration is important to avoid a protamine reaction and hypotension.

Following acceptable hemostasis at all anastomoses and surgical sites in the thorax, the chest is then closed. In most cases, the patient will then be transported directly to the ICU intubated. However, for uncomplicated surgeries where the patients are not on significant support, extubation in the OR is being increasingly considered. This decision should be made following close communication with the surgical team.

Postoperative Management and Complications of CABG

For isolated CABG's, current Society of Thoracic Surgeons (STS) metrics call for rapid wake-up and extubation within 24 h of leaving the operating room. The anesthesiologist should be mindful of these goals when administering additional paralytic, analgesic or amnestic agents towards the end of the case.

A multitude of complications of CABG must be surveilled in the immediate postoperative period. Complications include post-cardiotomy ventricular failure, post-operative bleeding and need for emergent re-exploration, post-perfusion syndrome, atrial and ventricular arrhythmias, stroke, pleural effusions and infection. Initial monitoring for these complications is recommended to occur in the ICU setting where 1:2 nurse to patient ratio and continuous central monitoring of vital signs is available. This is changing with minimally invasive procedures that may be fast-tracked to standard surgical ward care, but for procedures requiring sternotomy ICU recovery remains recommended.

Off-Pump Coronary Artery Bypass Grafting (OPCAB)

Surgical Principles

Many of the details of pre-, intra- and post-operative management are similar between on-pump and off-pump procedures. We will discuss the relevant differences (summarized in Table 1.3), but otherwise it should otherwise be assumed that management is the same as described above. The core principle of the OPCAB is to avoid the complications of vasoplegia, myocardial stunning and ventricular failure that result from CPB. Additional benefits may include reduced bleeding due to less hemodilution and lower level of heparinization, along with bypass-induced consumptive coagulopathy. The overall benefit of the OPCAB is controversial although there is data to demonstrate improved outcomes in certain high-risk patients [23].

The technique for OPCAB involves positioning the beating heart to allow exposure of the affected vessel and stabilizing the small portion of the beating heart required to make an individual distal anastomosis. A variety of commercial devices are available, but fundamentally utilize external suction on the heart to position the apex in any permutation—including lifted up and out of the chest to expose the back of the heart. The vessel is then exposed and a suction device placed on either side of the vessel to hold that small portion of the heart in place. The distal end of the graft is then sewn to the vessel. Because blood is still being supplied to the coronary, a tourniquet is placed proximal to the anastomosis to prevent bleeding when the artery is opened. This tourniquet may induce ischemia in the supplied territory. Holding the heart in abnormal positions as

Table 1.3 Major differences in anesthetic management of CABG and OPCAB

Item	CABG on CPB	OPCAB
Temperature management	Passive hypothermia pre-bypass, active hypothermia on pump, aggressive active re-warming just before and after separation	Maintain normothermia with active warming through entire case
Fluid management	Minimize fluid administration to minimize hemodilution prior to bypass run	Maintain euvolemia early in case, often patients require additional preload before manipulating heart
Anticoagulation	Heparinization titrated to ACT >400 s. Loading of antifibrinolytic	Reduced heparin administration titrated to ACT goal usually >300 s
Monitoring	TEE useful for multiple phases, especially for separation from CPB. PAC only for low EF, high risk of post-bypass dysfunction, or pulmonary morbidities	TEE valuable for initial volume assessment, but limited utility during manipulation of heart. PAC may help manage pre-load during manipulations
Pressors and inotropes	Expect higher pressors and inotrope requirements post-bypass due to stunning and vasoplegia	After revascularization, pressor and inotrope requirements often rapidly reduced/weaned. Infrequent need for inotropes

is required to expose target coronaries may also impede inflow or outflow through the great vessels. The management of these often-encountered complications is discussed later in this chapter. Generally, the free end of the IMA (if it is used) is anastomosed first, usually to the LAD, which allows for early re-perfusion of a critical portion of the myocardium before continuing with the rest of the procedure.

Once the distal ends of all grafts are sewn, the heart is returned to its normal position and the surgeon will ask for the blood pressure to be reduced for work on the aortic (proximal) anastomoses. In order to gain a bloodless field, the surgeon may place a partial aortic clamp ("J-clamp"). An alternative to this clamp is the Maquet Heartstring™ device which allows puncture of the aorta and anastomosis around the hole without bleeding via a removable occluder on the luminal side of the hole. Once all proximal anastomoses are made, any clamps are removed restoring flow through the grafts, and all distal and proximal anastomoses are re-examined for integrity. This may involve lifting the heart manually for inspection of posterior anastomoses.

Selection of Ideal Surgical Candidates

As previously stated, the differences in outcome between techniques are generally equivocal although there is some benefit in high-risk patients with multiple co-morbidities. Patients in whom aortic cross-clamp is also risky due to high-grade atherosclerotic disease of the aorta may also benefit from OPCAB.

There might be a trend towards reduced stroke with OPCAB. A multitude of comparative studies have been performed, but even recent studies have reached different conclusions. In a randomized controlled trial published in 2009 that enrolled 2203 patients (VA population), there was no significant difference in neuropsychological outcomes between the techniques, and on-pump CABG showed better graft survival and overall outcomes [24]. Conversely, a 2016 meta-analysis of randomized controlled trials analyzed 16,904 patients in 51 studies and concluded that on-pump surgery was associated with an increased occurrence of stroke [25]. Because there may be a higher likelihood that grafts will be patent years out from surgery with on-pump CABG [24, 26], older patients may be the population that benefits most from OPCAB both because they are at a higher risk of perioperative stroke and postoperative cognitive dysfunction, and because the grafts do not need to survive as long as in younger patients.

Predictably, manipulating the heart with non-anatomic positioning will significantly affect heart filling and function. This positioning is usually tolerated with appropriate management assuming that the heart has sufficient reserve to tolerate the hemodynamic swings. Generally, those with preserved ejection fraction (>40–45%) tolerate this well, but occasionally conversion to CPB is required if attempts to reposition the heart fail. Thoughtful consideration about who is likely to tolerate this manipulation is important as emergent conversion to CPB is associated with an increased mortality rate [27].

Additionally, despite the stabilization devices, movement at the anastomosis site can still make sewing difficult, and small or tortuous vessels may be especially difficult for the surgeon to find and adequately stabilize. Placing a tourniquet on vessels with high-grade or very proximal lesions (e.g. left main) may also be contraindicated. Finally, surgeon experience and comfort with the technique are variable and given the generally equivocal differences in outcome, many continue to prefer on-pump techniques.

Intraoperative Anesthetic Management

Most steps in the surgical procedure are the same as with CABG until the administration of heparin. The purpose of administering heparin in OPCAB is to prevent blood from coagulating in grafts and low-flow vessels during the anastomotic period. This approach requires a lower level of anticoagulation than that needed to prevent clotting within a bypass circuit. Typically, half the dose of heparin is given with a target ACT typically greater than 300 s. It is the role of the anesthesiologist to manage ongoing dosing of anticoagulation, typically by measurement of an ACT every half hour. Antifibrinolytic infusions are generally not utilized. Prevention of hypo-