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Operative Cardiac Surgery

SIXTH EDITION

Edited by

Thomas L. Spray and Michael A. Acker

CRC Press
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Prologue

The Rob & Smith's Operative Surgery series established a legacy of texts focusing on the critical element of all surgical fields — the operative procedure itself. Specialization and even sub-specialization of surgery practice has led to growing number of editions in the Operative Surgery series, resulting in a broad dissemination of texts from experienced surgeon-leaders sharing their surgical skills by demonstrating how they perform the subject operation. This central goal continues to be the focus of Operative Surgery texts: thoroughly described and carefully illustrated major surgical procedures.

Even in the current multi-media environment with access to videos of surgical procedures, the unique value of these Operative Surgery texts persist. Individual chapters on all major operations performed in the particular specialty area provide the reader with exposure to leading surgeons' full clinical and technical skills and experience. This expert commentary combined with precise and detailed illustrations maintain the special relevance of Operative Surgery texts.

This 6th Edition of Operative Cardiac Surgery, being published only 14 years after the previous edition, reflects the continued swift refinement and evolution of adult and congenital heart surgery. Progress, improvement and the development of new procedures in cardiac surgery are marked by single decades. The rapid progress that challenges cardiac surgeons to learn, enhance and refine their surgical skills has been incorporated in this 6th Edition.

While the role of the surgeon encompasses the full span of the encounter with the patient, including diagnostic, peri- and post-operative management, the singular essential role he or she plays is in the performance of the operation. How to carry out the operation safely and effectively is the essential element of the surgeon's responsibility. This new Operative Cardiac Surgery textbook is an invaluable volume by expert surgeons for the benefit of other surgeons. It is intended for surgeons who aspire to the best surgical outcomes for their patients, based on the most current and successful surgical techniques. Congratulations to the Editors, Michael Acker and Thomas Spray, for this updated 6th Edition. The many contributors deserve special acknowledgement and thanks for their efforts and expertise. The entire cardiac surgery community, and our patients, are the beneficiaries of this outstanding text.

Timothy J. Gardner


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Preface

It has been 14 years since the publication of the 5th Edition of *Operative Cardiac Surgery* by Gardner and Spray. The 5th Edition contained 60 separate chapters dealing with the full spectrum of adult and pediatric cardiac surgery techniques and procedures that encompassed the specialty in the early 2000s. In order to encompass the entire range of adult and pediatric cardiac surgery today, the 6th Edition contains 68 chapters reflecting the progress of cardiac surgery in multiple areas over the past 14 years.

The section on surgery for ischemic heart disease now includes a new chapter on robotic total endoscopic coronary artery grafting (TECAB). The section on valvular heart disease has been expanded to include new chapters on TAVR, valve sparing aortic root replacement and tricuspid valve surgery. The section on heart failure has been expanded to include a new chapter on temporary mechanical assistance, including ECMO for the treatment of cardiogenic shock, and surgery for hypertrophic cardiomyopathy. We have also decided to include a chapter on lung transplantation since lung transplantation is done largely by cardiothoracic surgeons today. The section on thoracic aortic disease has been expanded to include new chapters on thoracic endovascular aortic repair (TEVAR), hybrid aortic arch repair, as well as including a discussion on Type B aortic dissections. Finally, the section on cardiac rhythm disorders now includes a separate chapter on the Maze procedure for the treatment of atrial fibrillation. In addition to these many new chapters, all our chapters have been largely rewritten with new illustrations and by a new set of authors who are currently experts in the field.

In the section on congenital heart disease, the previous chapters from the 5th Edition have remained and new chapters have been added on aortic pulmonary window; cardiac transplantation for congenital heart disease; lung and heart/lung transplantation for congenital heart disease; ventricular assist devices for congenital heart disease; congenital mitral valve repair and aortic valve repair.

The new edition continues to distinguish itself in its outstanding illustrations that accompany every chapter with detailed descriptions of the operative procedures. This addition continues the tradition of utilizing brilliant art work and illustrations that clearly reflect the anatomic and technical features of each operative procedure.

Dr. Spray and I are honored to have had the opportunity to edit the 6th Edition with such a renowned and respected group of authors. We thank all our editors and contributors to this work knowing that it has been a long time in coming. I specifically want to thank Miranda Bromage for her superb leadership in shepherding this large project to the finish line.

Thomas L Spray, MD
Michael Acker, MD


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SECTION

Perioperative management


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1

Echocardiography for cardiac surgery

JARED W. FEINMAN, BONNIE L. MILAS, AND JOSEPH S. SAVINO

HISTORY

The ability to perform real-time cardiovascular imaging in the operating room using transesophageal echocardiography (TEE) has been the most important diagnostic advancement in cardiac surgery over the past 30 years. TEE was developed in the mid 1970s but did not enter widespread use until the early 1980s when flexible TEE probes with manipulatable tips became available. The early probes were only capable of imaging along a single plane (monoplane), which somewhat limited their utility. The technology behind ultrasound image acquisition has moved forward rapidly, however, to the point that modern TEE probes can image along a 180 degree axis, display multiple imaging planes simultaneously (x plane imaging) and acquire large pyramids of data that allow real-time, three-dimensional (3D) rendering of cardiac structures. As intraoperative TEE use has become commonplace, there has been a joint effort by the American Society of Echocardiography (ASE) and the Society of Cardiovascular Anesthesiologists (SCA) to standardize the perioperative TEE examination through the issuance of joint guideline statements as well as the establishment of a board certification process administered by the non-profit National Board of Echocardiography. The first set of guidelines on performing a comprehensive TEE exam was issued in 1999, and consisted of 20 standard echocardiographic views. This was expanded to 28 two-dimensional (2D) views and a focused 3D exam in the most recent 2013 update. Current recommendations state that an intraoperative TEE should be performed (barring a contraindication) in all patients undergoing open heart, thoracic aorta, or catheter-based cardiac surgery, in most patients having coronary artery bypass grafting (CABG), and in any patients having non-cardiac surgery with known or suspected cardiac pathology that may impact outcomes.

PRINCIPLES AND JUSTIFICATION

A few general principles regarding image generation, interpretation of data, and limitations of the ultrasound system are useful in understanding TEE in the operating room. In basic terms, the ultrasound transducer uses piezoelectric crystals to convert electrical energy into high-frequency acoustic energy (ultrasound waves) and vice versa. The ultrasound waves that are emitted from the transducer travel through tissue planes where they can be absorbed (converted into heat), refracted (if crossing between objects with different propagation speeds), or reflected (if adjacent media have different acoustic impedances) back towards the probe where they are converted by the ultrasound system into an image. Since reflection occurs best at a 90-degree angle, 2D imaging will be most effective when the ultrasound beam is orthogonal to the tissue being imaged. Also, any material that causes a lot of reflection (e.g. prosthetic valves and calcium deposits) will not allow the ultrasound beam to pass beyond it, impairing the ability to image more distant structures. The data being reflected back to the ultrasound probe can be expressed in two different imaging formats. The most common is 2D B-mode imaging, where a line of echo data is moved back and forth in an arc through a section of tissue and displayed so that a continuous 2D image is generated. Alternatively, in M-mode imaging a single scan line is displayed over time, which allows for a very high frame rate and accuracy of linear measurements. Modern, full matrix array transducers have about 3000 independent piezoelectric elements that can be fired in a phased manner to generate a radially propagating scan line. The scan line can be steered in three planes to generate a true 3D volume of data, which can either be displayed in real time or stitched together with adjected volumes using ECG-gating to produce an even larger volume of 3D data.

Doppler ultrasound can be used to assess the velocity of blood flow or tissue movement within the heart and vascular structures. Since this form of imaging relies on the Doppler shift equation:

$$\text{Doppler shift} = \frac{(2 \times \text{velocity of object} \times \text{incident frequency} \times \text{cosine } \theta)}{\text{Propagation speed of ultrasound}}$$

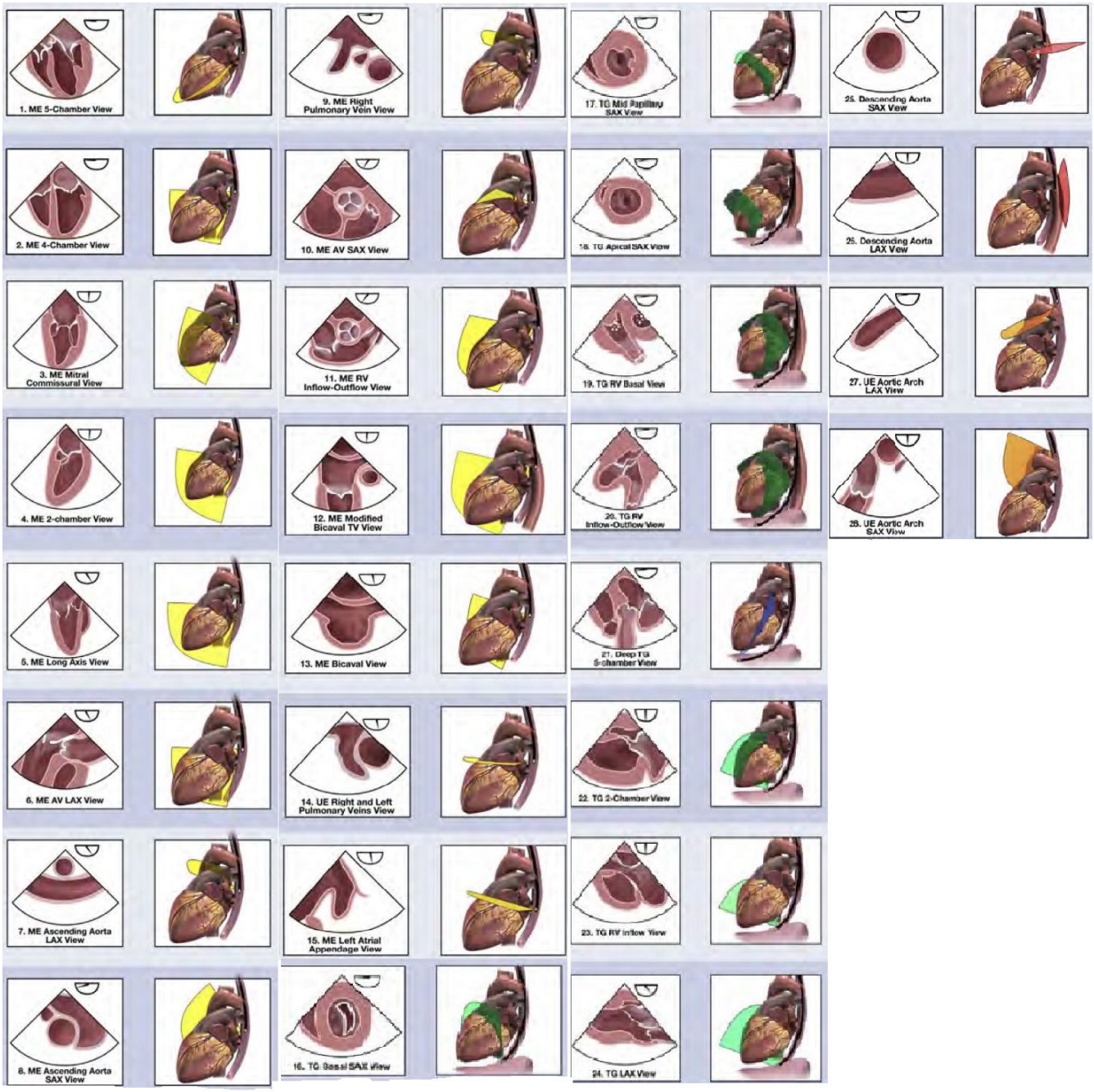
a calculated velocity will be most accurate when the ultrasound beam is perfectly aligned with the blood flow being assessed (cosine 0° = 1), and should only be used if θ is <20 degrees. This stands in contrast to the aforementioned 2D imaging, which will achieve the best resolution when the structure being imaged is orthogonal to the ultrasound beam. Doppler imaging is used in three common modes: pulsed-wave Doppler, continuous-wave Doppler, and color-flow Doppler. Pulsed-wave and continuous-wave Doppler imaging both assess the velocity of the object being imaged over time, but differ in that the former is limited in the maximum velocity that can be assessed (Nyquist limit) but has range specificity, while the latter is not limited by a maximum velocity but has range ambiguity. Thus, pulsed-wave Doppler is used to assess low-velocity flow in a specific location (e.g. pulmonary vein flow, transmitral inflow in a non-stenotic valve) while continuous-wave Doppler is useful in assessing high-velocity flow through a stenotic or regurgitant valve. Color-flow Doppler imaging overlays pulsed-wave Doppler data on a standard 2D image to generate a color map that provides information on the direction of blood flow as well as semi-quantitative information on the mean velocities of flow. Traditionally, blue denotes movement away from the ultrasound probe and red movement towards the probe.

The TEE probe itself is essentially a modified gastroscope with a matrix array of piezoelectric crystals at the tip in place of a camera. Probe insertion and manipulation may lead to significant injury, and precautions are necessary to minimize the risk. Most perioperative TEEs are performed in anesthetized and intubated patients who cannot respond to pain or discomfort caused by excessive probe impingement of soft tissue. Before insertion, the TEE probe is inspected for damage or any break in the encasement. Then the probe is lubricated, inserted into the mouth, and passed posteriorly into the esophagus, and most imaging occurs at the level of the midesophagus, upper esophagus, or stomach. Manufacturers' recommendations for probe cleaning and maintenance should be followed with a systematic approach to instrument processing. Complications from probe insertion are uncommon (0.2% in one case series of 7200 patients reported by Kallmeyer et al.), and range from minor trauma to the teeth or pharynx to esophageal perforation, which carries with it a high risk of mortality.

Contraindications to TEE are disorders of the mouth, esophagus, or stomach that could preclude safe passage of the probe. These include esophageal strictures, diverticula, or webs, cancerous masses, or an active esophageal perforation or bleed. Abnormal displacement of the esophagus, such as may occur with a large aortic aneurysm, is not a contraindication, but is associated with increased risk. In patients where there is a question of esophageal disease, the risks and benefits of TEE for that specific procedure must be weighed. If TEE is to be performed, it may be prudent to first have an esophagogastroduodenoscopy (EGD) done in the operating room to make sure that placement is safe, and/or to use a pediatric TEE probe, which is much smaller in diameter than a standard adult probe but comes with significant imaging limitations.

COMPREHENSIVE TEE EXAMINATION

The current ASE/SCA guideline statement on performing a comprehensive TEE examination lists 28 standard views with additional 2D and 3D imaging performed as needed (see **Figure 1.1**). The TEE probe is initially inserted to a depth of approximately 30 cm and the entirety of the examination is performed by adjusting the rotation of the beam within the probe (omniplane angle), rotating the probe itself to the left or right, or moving the probe farther into or out of the esophagus/stomach. The views and the corresponding approximate omniplane angle (between 0° and 180°) for each view are illustrated in the figure. The order in which a TEE exam is conducted varies between individual providers. While there is no "ideal" order of imaging, it is important for an echocardiographer to choose a protocol and follow it in every case, as this will prevent any unanticipated findings from being missed. When discussing standard TEE views, the nomenclature is such that each view is named for the location of the probe in space (e.g. upper esophageal (UE), midesophageal (ME), or transgastric (TG)) followed by what is being imaged (four-chamber, two-chamber, etc.). Figure 1.1 has been reproduced with permission from Hahn RT, Abraham T, Adams MS, et al. Guidelines for performing a comprehensive transesophageal echocardiographic examination: recommendations from the American Society of Echocardiography and the Society of Cardiovascular Anesthesiologists. *J Am Soc Echocardiogr.* 2013; 26: 921–64.



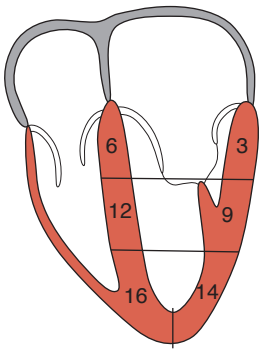
1.1 TEE examination standard views.

Left ventricle

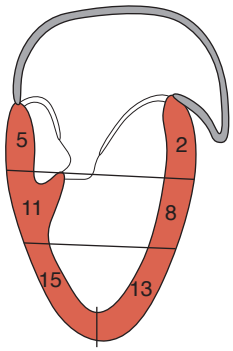
The left ventricle (LV) can be divided into a series of segments that allows correlation of regional wall motion with abnormalities in coronary blood flow. There are currently two commonly used models of left ventricular anatomy: the 16-segment model and the 17-segment model. The only difference between the two is that the former divides the apex of the heart into anterior, lateral, inferior, and septal regions, while the latter adds a fifth segment, the apical cap, made up of the myocardium beyond the end of the LV cavity.

The longitudinal axis of the LV is described as basal, mid, or apical. The midesophageal four-chamber view shows the three inferoseptal and three anterolateral segments (**Figure 1.2a**). Midesophageal two-chamber views show the three anterior and three inferior segments (**Figure 1.2b**) and midesophageal long-axis (LAX) views show the two anteroseptal and two inferolateral segments (**Figure 1.2c**). TG short-axis (SAX) views show all six segments at the mid (**Figure 1.2d**) and basal (**Figure 1.2e**) levels, and all four segments at the apical level. These figures have been reproduced with permission from Shanewise JS, Cheung AT, Aronson S, et al. ASE/SCA guidelines for performing a comprehensive intraoperative multiplane transesophageal echocardiography examination: recommendations of the American Society of Echocardiography Council for Intraoperative Echocardiography and the Society of Cardiovascular Anesthesiologists Task Force for Certification in Perioperative Transesophageal Echocardiography. *Anesth Analg.* 1999; 89: 870–84, and *J Am Soc Echocardiogr.* 1999; 12: 884–900.

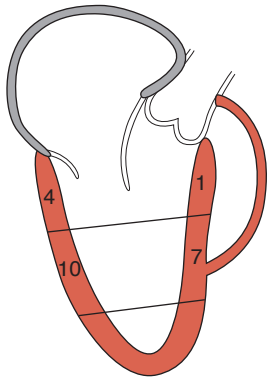
See also **Figures 1.3–1.7**.



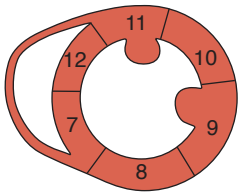
a. ME four-chamber view



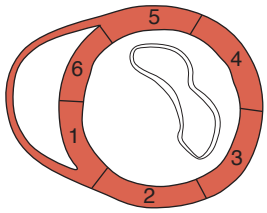
b. ME two-chamber view



c. ME long-axis view



d. TG mid-short-axis view

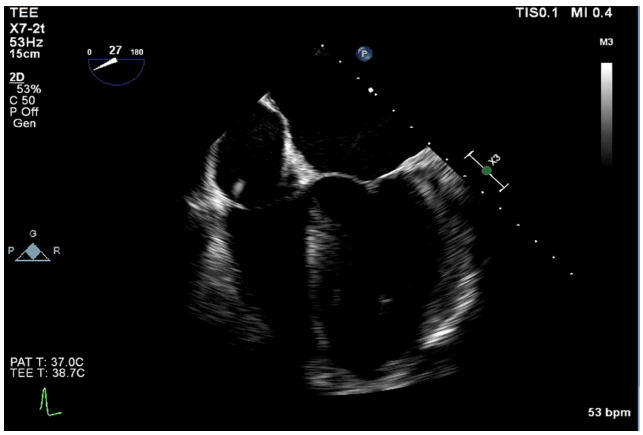


e. TG basal short-axis view

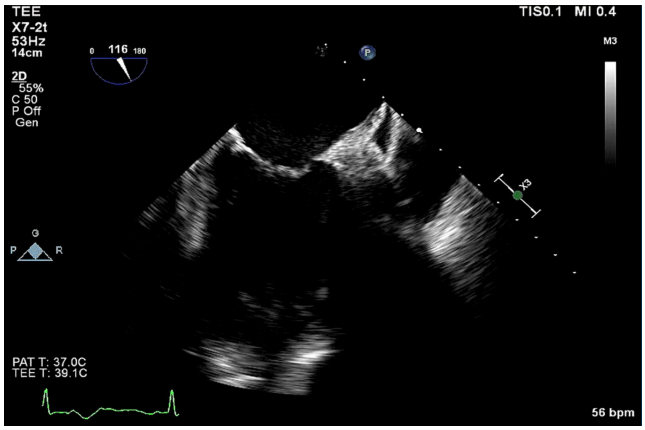
Key

Basal segments	Mid segments	Apical segments
1 = Basal anteroseptal	7 = Mid anteroseptal	13 = Apical anterior
2 = Basal anterior	8 = Mid anterior	14 = Apical lateral
3 = Basal anterolateral	9 = Mid anterolateral	15 = Apical inferior
4 = Basal inferolateral	10 = Mid inferolateral	16 = Apical septal
5 = Basal inferior	11 = Mid inferior	
6 = Basal inferoseptal	12 = Mid inferoseptal	

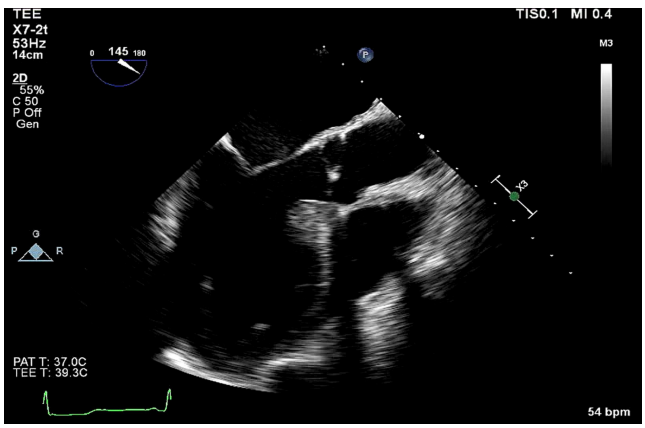
1.2a–e



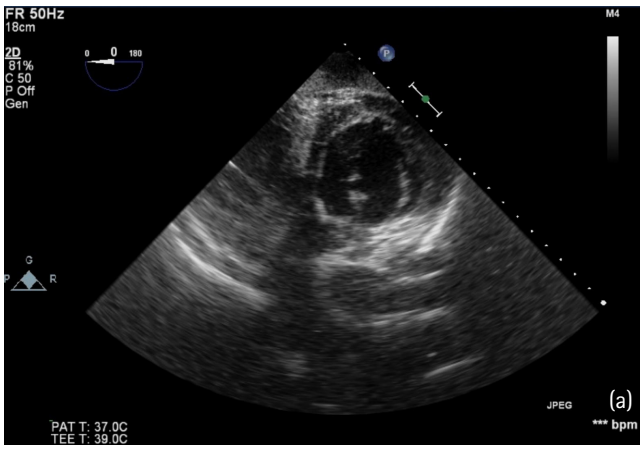
1.3 LV midesophageal four-chamber view.

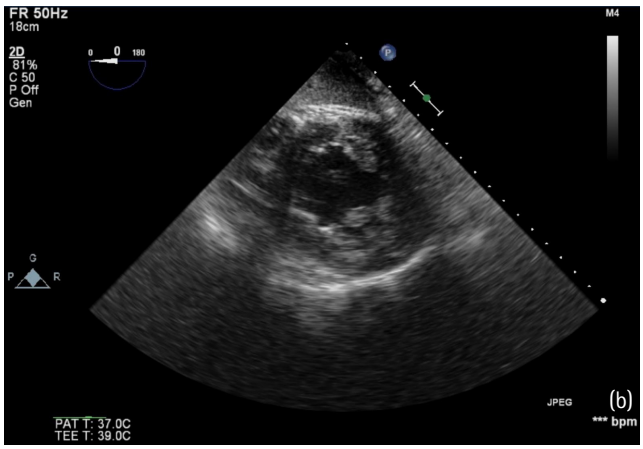


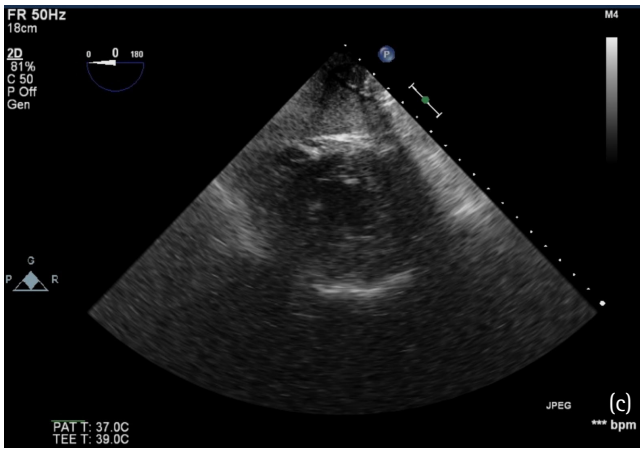
1.4 LV midesophageal two-chamber view.



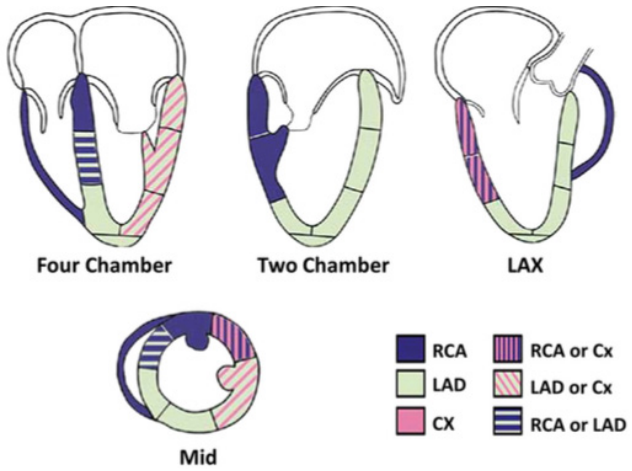
1.5 LV midesophageal long-axis view.







1.6a–c LV transgastric short-axis views: (a) basal, (b) mid papillary, and (c) apical.



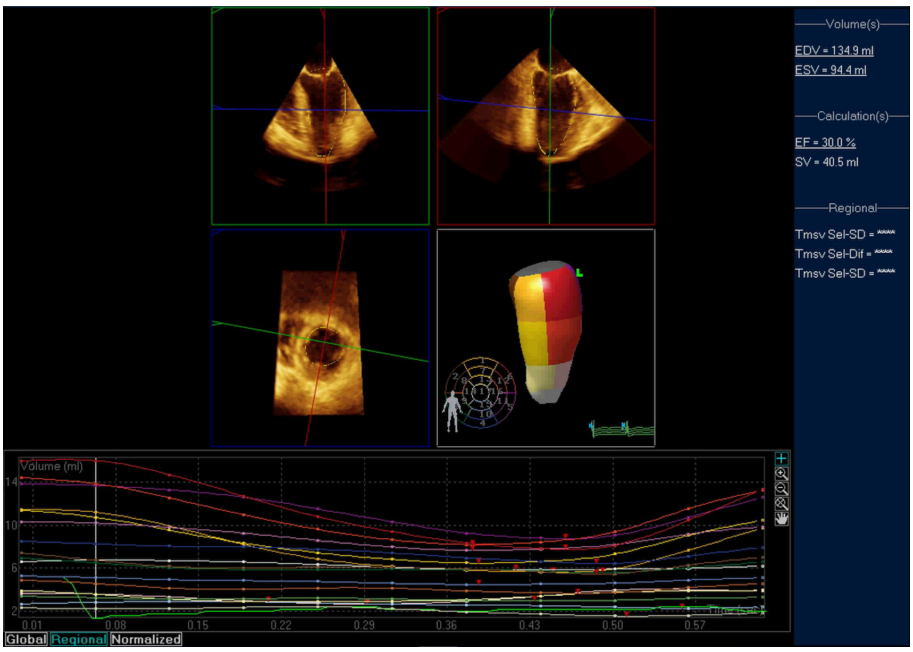
1.7 Coronary perfusion pattern of the LV. This figure has been reproduced with permission from Lang RM, Badano LP, Mor-Avi V, et al. Recommendations for cardiac chamber quantification in adults: an update from the ASE and EACVI. *J Am Soc Echocardiogr.* 2015; 28: 1–39.

Left ventricular wall motion is scored based on wall thickening and the degree of endocardial excursion using the following scale: normal (wall thickening greater than 30%), mild hypokinesis (10–30%), severe hypokinesis (<10%), akinesis (no thickening), and dyskinesis (paradoxical motion). Wall motion can be abnormal globally (as in dilated cardiomyopathy) or regionally. The latter is usually related to myocardial ischemia or infarction, but may accompany less common diagnoses such as sarcoidosis, myocarditis, and takotsubo cardiomyopathy. Over time, ischemic segments may become thinned and echogenic due to fibrosis and scarring and can even progress to aneurysm formation. In addition to regional function, the global function of the LV is assessed, most commonly by ejection fraction (EF), which is equivalent to:

(LV end-diastolic volme – LV end-systolic volume) / (LV end-diastolic volume) × 100%

An EF of <50% is considered abnormal, although a normal EF does not exclude reduced cardiac function in the setting of significant mitral regurgitation (MR) or isolated regional wall motion abnormalities. LV global function is frequently assessed qualitatively via "eye-balling" an EF, but quantitative measurements of LV function are possible. These include simple 2D measurements such as fractional area change (FAC) (end diastolic area - end systolic area / end diastolic area) or more complex volumetric assessments like the Simpson's method of disks, in which the endocardial border of the LV is traced in systole and diastole and the volume of blood in the LV and EF are calculated automatically by dividing the LV into a bullet-shaped stack of disks whose volumes are summed.

Three-dimensional echocardiography (3D TEE) (**Figure 1.8**) has allowed for increasingly accurate calculations of LV volumes and EF compared with 2D TEE, as well as made detecting regional wall motion abnormalities more quantitative. The use of global longitudinal strain also shows promise as a quantitative measure of LV function and may even have a role in unmasking problems with LV function before there is a decrement in EF. However, more studies are still necessary to understand when strain measurement is most useful, especially in TEE as opposed to transthoracic echocardiography (TTE).



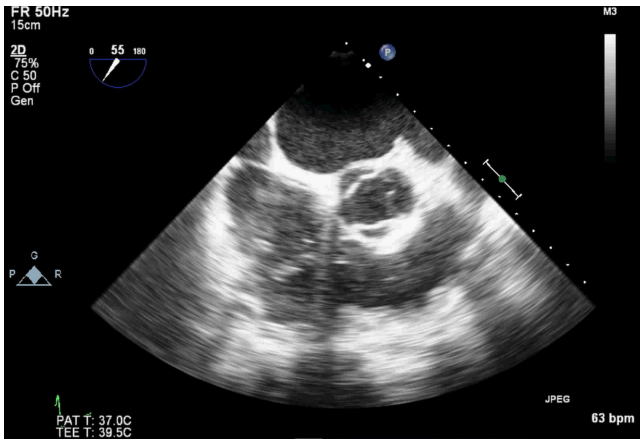
1.8 3D LV analysis using the QLab software from Philips, Inc.

Right ventricle

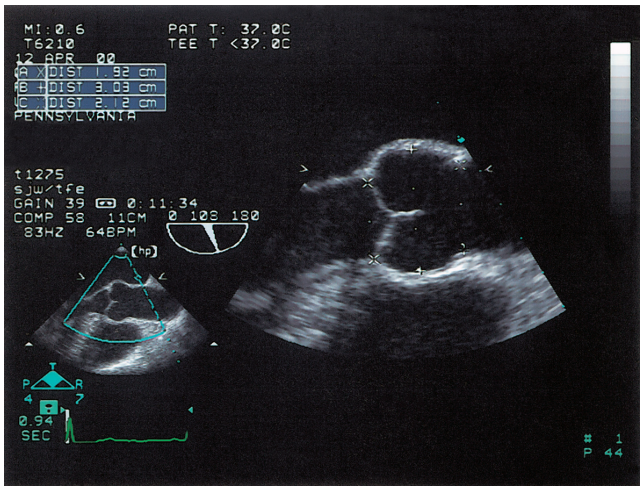
The right ventricle (RV) has a crescentic shape and is located anteriorly (farther from the imaging probe in TEE), which makes both qualitative and quantitative assessments of its function difficult. Standard TEE views for interrogating the RV include the midesophageal four-chamber view (see **Figure 1.3**), the midesophageal RV inflow–outflow view (**Figure 1.9**), the transgastric RV basal view, and the transgastric RV inflow view. RV function is commonly assessed qualitatively as normal or mildly, moderately, or severely hypokinetic based on looking at the motion of the RV free wall, the RV outflow tract, the RV septal wall, and the movement of the tricuspid annulus during the cardiac cycle. There are a few quantitative measurements that can be made to assess RV contractility, including RV FAC and the tricuspid annular plane systolic excursion (TAPSE), but these have not been well studied in TEE. 3D echocardiographic assessment of the RV is possible using offline software that allows recreation of the crescentic shape of the RV and semi-automates calculation of RV EF, which has been shown in a few studies to correlate well with cardiac MRI imaging, but this software is not yet widely available in the operating room. In a similar way to the LV, RV strain has been looked at in some TTE studies and demonstrated good reproducibility and predictive ability, but much more work remains to be done before this methodology is widely adopted.

Aortic valve, aortic root, and left ventricular outflow tract

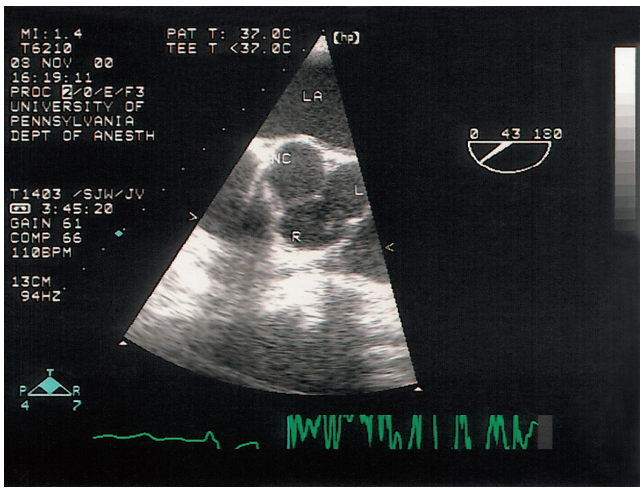
The aortic valve (AV) is examined in long-axis (**Figure 1.10**) and short-axis (**Figure 1.11**) views with and without color Doppler in all patients. This allows the echocardiographer to visualize all three cusps and determine if any aortic regurgitation (AR) or aortic stenosis (AS) is present. While most AVs are trileaflet, bicuspid valves are present in about 2% of the population, and unicuspid and quadricuspid valves are possible. From the long-axis view, the diameter of the AV annulus, the sinuses of Valsalva, the sinotubular junction (STJ), and the left ventricular outflow tract (LVOT) are measured. These are helpful for surgical planning and sizing of the AV prosthesis during aortic valve replacement (AVR). The deep TG view permits the echocardiographer to align the ultrasound Doppler beam with the flow of blood through the AV and LVOT so that velocities, and thus peak and mean gradients, can be calculated to grade the severity of AS.



1.9 Midesophageal RV inflow–outflow view.



1.10 Long-axis view of the aortic valve.



1.11 Short-axis view of the aortic valve.

AORTIC STENOSIS

Echocardiographic imaging in AS typically reveals areas of increased echogenicity representing leaflet calcification, immobile leaflets, and a small systolic orifice. Congenitally bicuspid valves develop stenosis at a higher rate and earlier in life than trileaflet valves, so are frequently seen in the OR (**Figure 1.12**). These valves have an elliptical, "fish-mouth" pattern appearance during systole in short axis. Patients may also have an "acquired" bicuspid valve, where one of the commissures has become calcified and fused, appearing similar to a raphae. Senile calcific AS and rheumatic AS appear similarly on TEE, and cannot be differentiated easily based on imaging alone. A close examination must also be made of the LVOT to rule out subaortic stenosis from a subvalvular membrane, systolic anterior motion (SAM) of the mitral valve, other congenital anomaly.

The severity of valvular stenosis (**Figure 1.13**) is determined by measurement of the transvalvular gradient and calculation of an aortic valve area. The maximum transaortic pressure gradient is calculated from the modified Bernoulli equation:

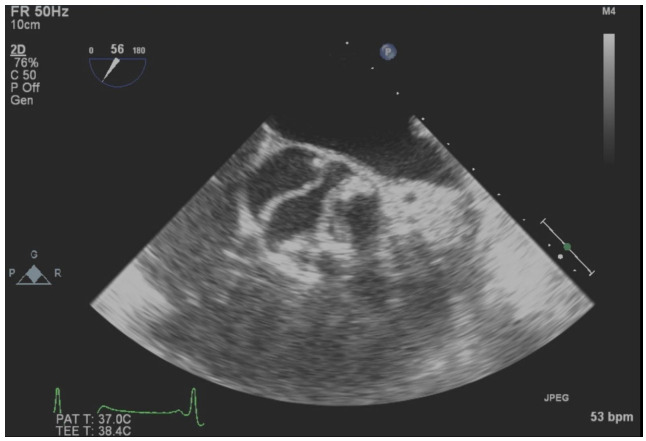
$$\text{Maximum gradient} = 4v^2$$

where v is the maximum velocity through the valve. This formula assumes that there is no flow acceleration in the LVOT from obstruction, SAM, or other etiology. If this is not the case, then the maximum velocity through the LVOT, obtained via pulsed-wave Doppler in the LVOT, must be factored into the equation. The presence of LVOT obstruction will also change the waveform of the continuous-wave velocity curve through the valve, giving it a dagger shape. The mean gradient is calculated by tracing the spectral envelope of the velocity curve and averaging the instantaneous gradients over the whole systolic ejection period. Pressure gradients are flow-dependent, and will be elevated when stroke volume is increased (e.g. pregnancy, exercise, AR) and reduced when stroke volume is decreased (e.g. hypovolemia, LV dysfunction, under general anesthesia).

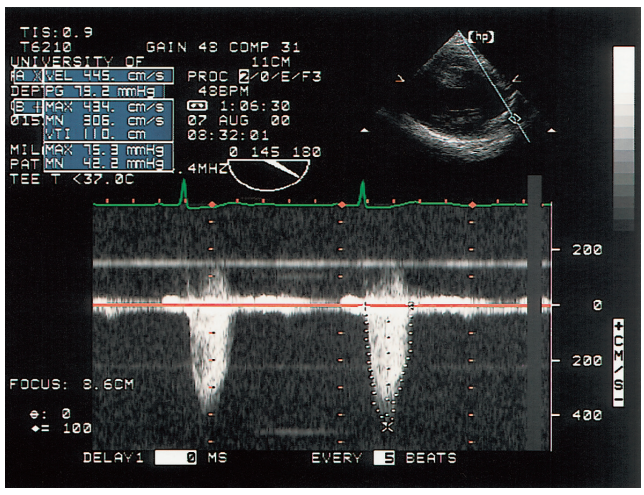
The AV area (AVA) can also be calculated from Doppler measurements using the continuity equation:

$$\text{AVA} = (\text{Area}_{\text{LVOT}} \times \text{VTI}_{\text{LVOT}}) / (\text{VTI}_{\text{AV}})$$

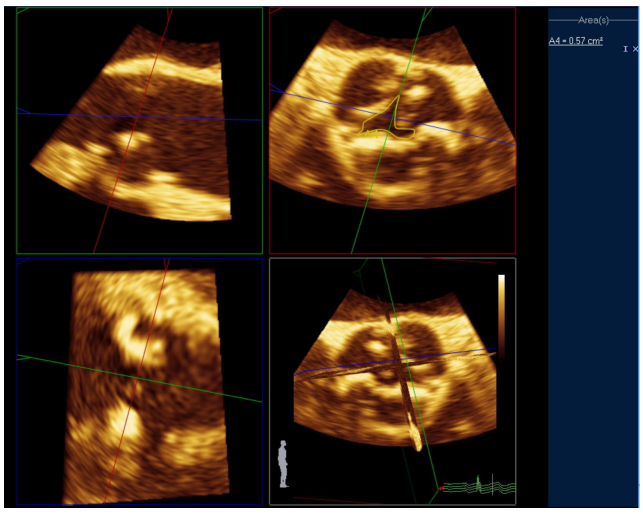
Error can easily be introduced into this calculation by misalignment of the Doppler flow with blood flow across the AV or LVOT, as well as in measurement of the LVOT diameter, where small errors will become large errors once squared to obtain the LVOT cross-sectional area. To overcome this, the LVOT area can be measured directly using 3D TEE. The AVA can also be directly measured using planimetry of the valve orifice in the midesophageal AV short-axis view, but this is not a very accurate measurement due to the elliptical nature of the AV. 3D planimetry of the AV orifice has been shown to be more accurate and reproducible than 2D planimetry (**Figure 1.14**).



1.12 Midesophageal AV short-axis view of a stenotic bicuspid valve.



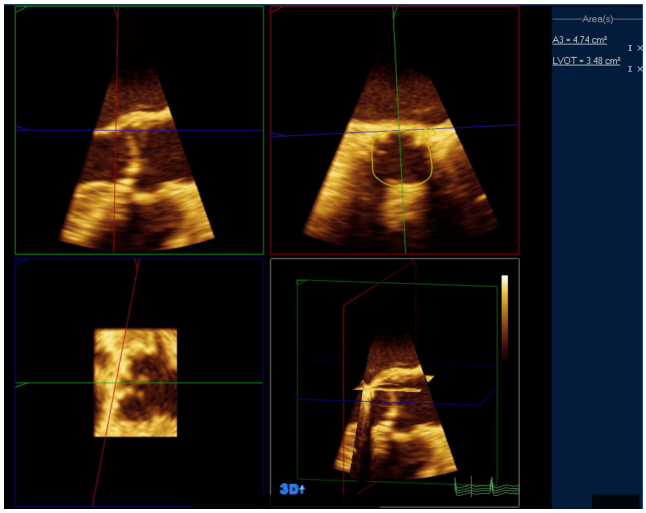
1.13 Continuous-wave Doppler through a stenotic AV.



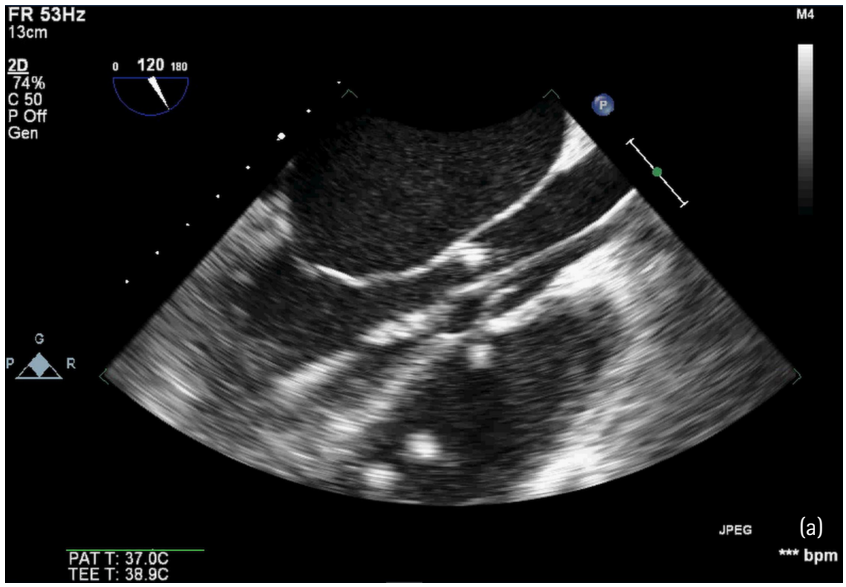
1.14 3D planimetry of a stenotic aortic valve area.

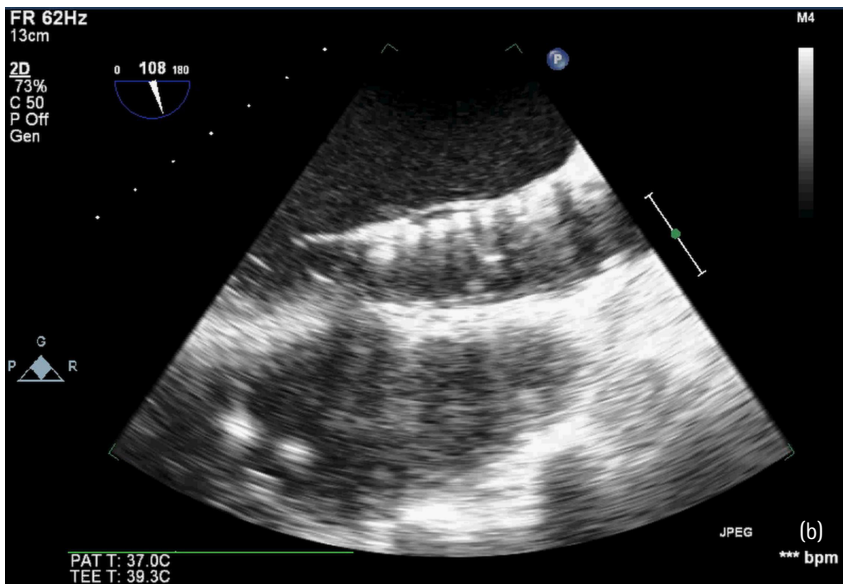
Traditionally, AS has been treated surgically by open AVR. This is rapidly changing, however, as more and more patients are treated endovascularly using transcatheter aortic valve replacement (TAVR). A wire is placed across the AV (**Figure 1.15a**), most commonly retrograde via the femoral artery (although transapical, transaxillary, and transaortic approaches are also used), and a valve is moved into position within the native, stenotic AV along this wire and finally deployed (**Figure 1.15b**), crushing the native leaflets between the new valve and the aortic wall. Paravalvular leaks are relatively common following TAVR, and must be assessed echocardiographically in the operating room via TTE or TEE.

Preoperative annular sizing is also essential in TAVR, as direct valve sizing during the procedure is impossible. This is often done using either 3D echocardiography or contrast-enhanced CT (**Figure 1.16**).



1.16 3D sizing of the aortic annulus.





1.15a, b Transcatheter aortic valve replacement (TAVR).

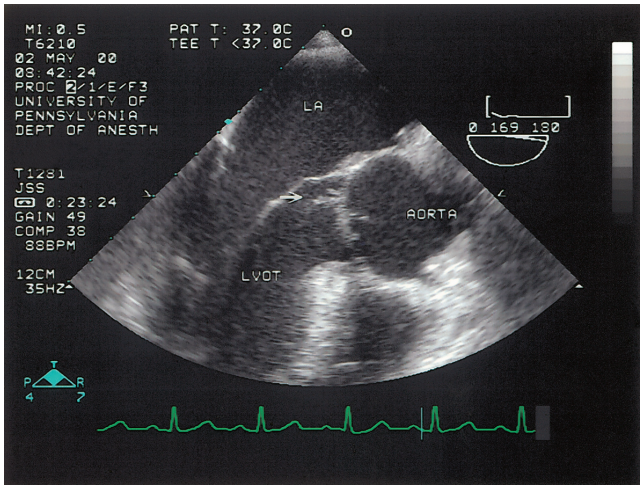
AORTIC REGURGITATION

The echocardiographic assessment of aortic regurgitation (AR) includes determination of the severity and etiology of the regurgitation, the effect of the regurgitant lesion on ventricular size and function, and the presence of associated findings. AR may be due to abnormalities of the aortic root, ascending aorta, or the valve cusps. AR is often seen in the setting of AS, as calcified, restricted leaflets have difficulty coapting during diastole.

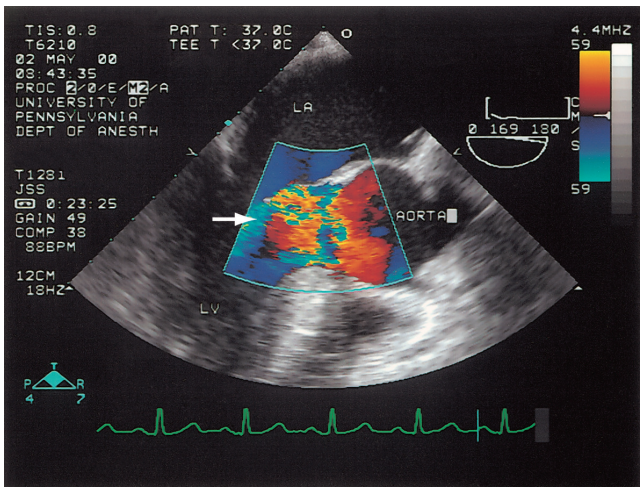
Myxomatous AV disease produces redundant, often prolapsing, cusps (**Figure 1.17**). Endocarditis produces AR through cusp or annular destruction and may be accompanied by vegetations and/or root abscesses (**Figure 1.18**).

Dilation of the aortic root and/or ascending aorta with normal cusp morphology can lead to AR owing to a lack of normal supporting structures (**Figure 1.19**). Causes of aortic root dilation include hypertension, collagen vascular disorders (e.g. Marfan syndrome, Ehlers–Danlos syndrome, Loeys–Dietz syndrome), rheumatoid arthritis, syphilitic aortitis, and poststenotic dilation associated with AS.

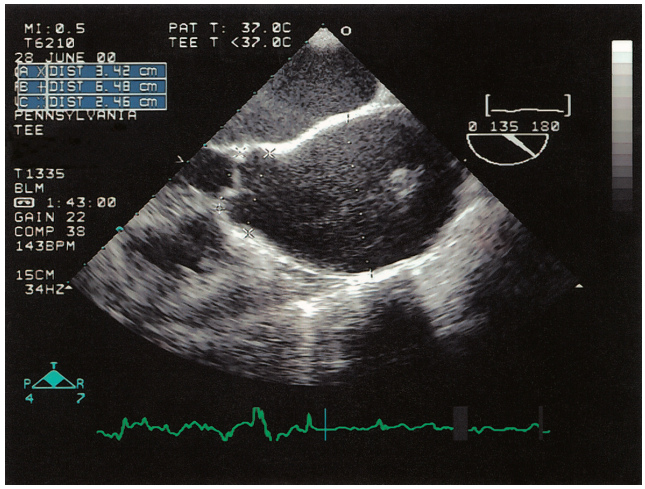
Aortic dissection produces an intimal flap in the lumen of the aorta and may produce AR by dilation of the aortic root, interruption of normal coaptation of the cusps by the intimal flap, or separation of one or more cusps from the aortic wall if the valve is involved in the dissection (**Figure 1.20**). In chronic AR, the LV responds to the volume load by slow, progressive dilation that eventually leads to a decrement in LV function. In acute AR (aortic dissection or AV endocarditis) the LV size may be normal but LV end-diastolic pressure may be elevated.



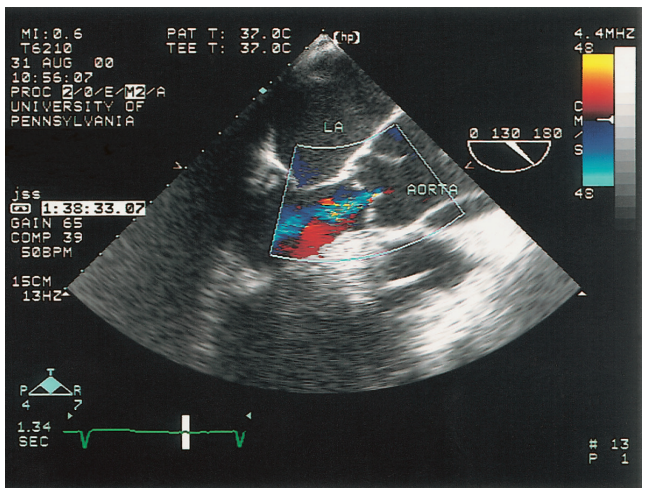
1.17 Midesophageal AV long-axis view demonstrating a prolapsing AV with vegetation (arrow).



1.18 Midesophageal AV long-axis view demonstrating severe AR (arrow).



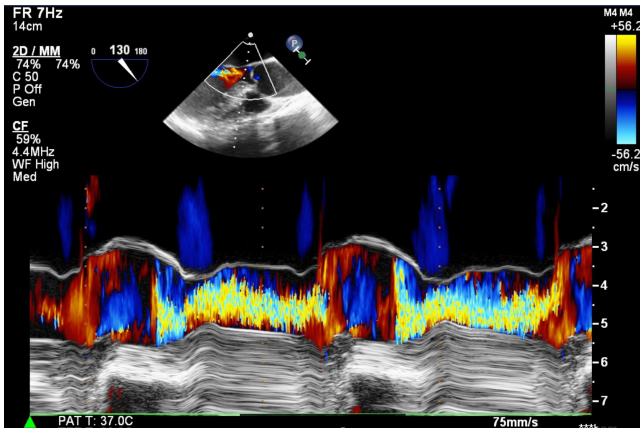
1.19 Midesophageal AV long-axis view demonstrating AR owing to aortic dilation.



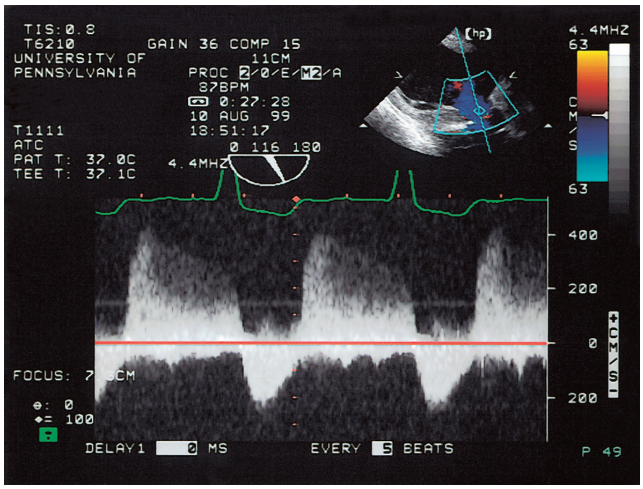
1.20 Midesophageal AV long-axis view of AR in the setting of a Type A aortic dissection.

AR severity is assessed in several ways, the simplest being the use of color Doppler across the LVOT and AV (**Figure 1.21**). The width of the AR jet can be compared to the width of the LVOT. If the jet is <25% of the LVOT width, then the AR is mild, 25–65% is moderate, and >65% of the LVOT width is severe AR. Additionally, the vena contracta, or smallest width of the AR jet at the level of the valve leaflets, can be measured, with a value of >0.6 cm corresponding to severe AR.

The continuous-wave Doppler spectral recording of AR typically reveals an increased velocity flow of 3–5 m/s (**Figure 1.22**). The rate of deceleration of the regurgitant jet corresponds to severity of AR, with aortic diastolic pressure decreasing more rapidly as AR worsens. Thus, the Doppler tracing can be used to calculate a pressure half-time (PHT) in milliseconds, with mild AR having a value of >500 ms and severe <200 ms. These measurements, however, can be affected by LV compliance and aortic pressure. Finally, pulsed-wave Doppler can be used in the proximal descending thoracic aorta (DTA) to look at blood flow during diastole. If there is holodiastolic reversal of flow in the DTA, this is pathognomonic for severe AR.



1.21 M-mode of the AR jet in the LVOT.



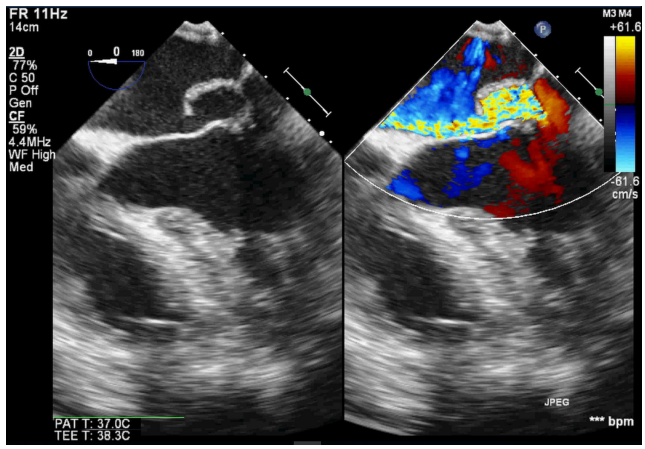
1.22 Transgastric long-axis view with continuous-wave Doppler producing high-velocity diastolic flow signal.

Mitral valve and left atrium

The move towards mitral valve (MV) repair in the majority of patients with degenerative MV disease was made possible, in part, by the widespread use of intraoperative TEE. TEE often provides a better view of the MV and left atrium (LA) than TTE due to the proximity of both structures to the esophagus. TEE allows for the rapid identification of annular calcification, prolapsing or restricted scallops, annular dilation, and the integrity of the subvalvular apparatus with high precision, which allows for better surgical planning before the initiation of cardiopulmonary bypass.

MITRAL REGURGITATION

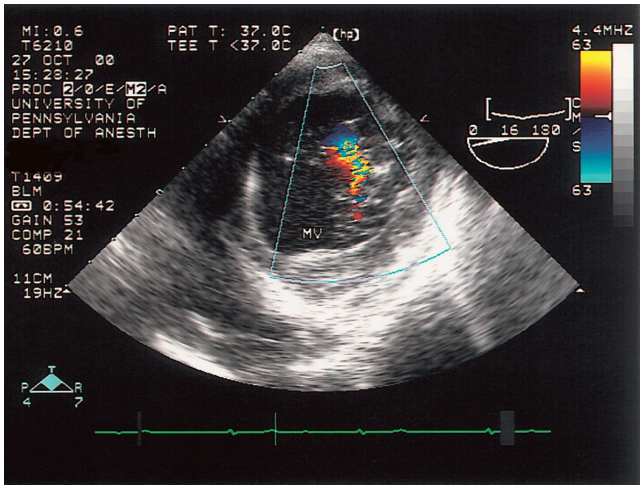
The most common etiologies of mitral regurgitation (MR) are myxomatous (degenerative) MV disease, ischemic heart disease, rheumatic heart disease, and endocarditis. Surgical correction of MR is guided primarily by the severity of the regurgitation, the etiology of the MR, and the anatomy of the leaflets and annulus. Severity of MR is assessed through several methods, most of which attempt to find an easily measurable surrogate for the effective regurgitant orifice area (EROA) of the valve. These include the vena contracta width and proximal isovelocity surface area (PISA) of the regurgitant jet, the ratio of jet area to LA area, and the presence or absence of systolic reversal of the pulmonary venous inflow. Determining the etiology of MR consists largely of looking for prolapsing or tethered (restricted) leaflets, as well as assessing for annular and LV dilation or the presence of perforations or clefts in the MV leaflets (**Figure 1.23**). Etiology has a big impact on the repairability of the valve. An isolated P2 prolapse can be repaired in nearly all cases, while a complex lesion with prolapse of multiple scallops on both leaflets and a cleft should only be repaired by a surgeon with sufficient experience in complex MV repairs; otherwise, valve replacement should probably be pursued.



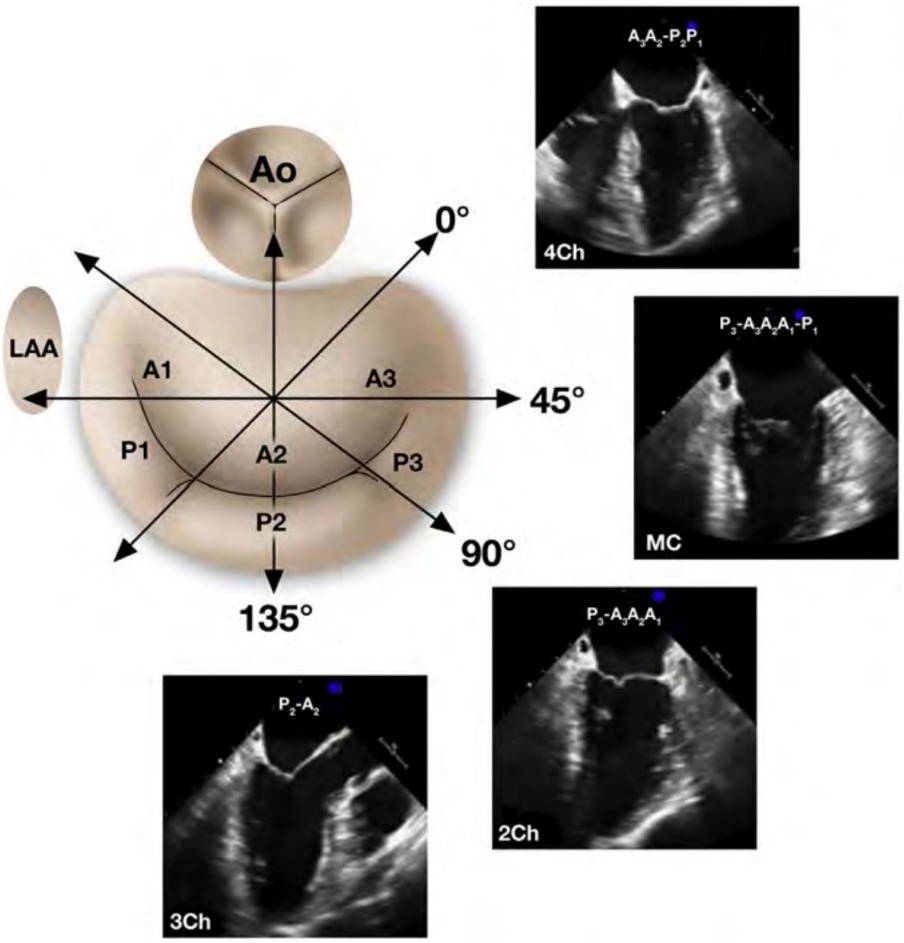
1.23 Midesophageal four-chamber view showing posterior (P2) leaflet flail and severe MR.

2D TEE assessment of the MV consists of four midesophageal views (shown in **Figure 1.24**) which cut the MV in such a way that, between these views, the six anterior (A1-3) and posterior (P1-3) scallops can be seen. The TG basal short-axis view (**Figure 1.25**) and TG two-chamber view are also useful in assessing MV pathology and examining the subvalvular apparatus.

3D TEE has been a major advance in the evaluation of MV disease. Using 3D echo, the entirety of the MV as well as the subvalvular apparatus can be visualized in real time from any angle. This allows for more rapid and accurate identification of prolapsing segments with less interobserver variability than 2D TEE. This is especially true for more complex valvular lesions. Color Doppler can also be added to 3D echo of the MV to help better identify the etiology of MR and more accurately grade the severity of MR using methods like vena contracta area and 3D PISA. Finally, there



1.25 Transgastric basal short-axis view.

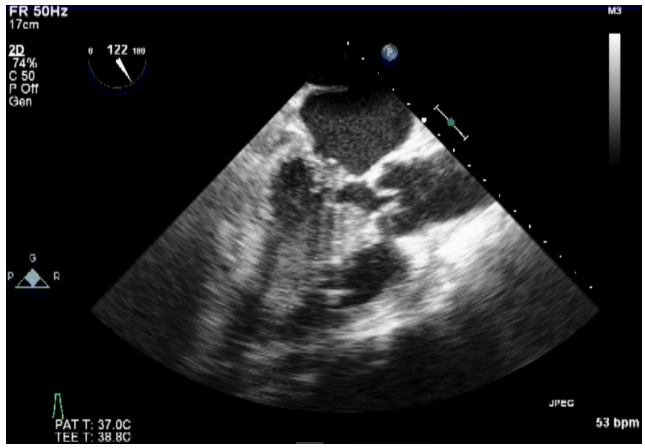


1.24 2D TEE midesophageal views of the mitral valve.

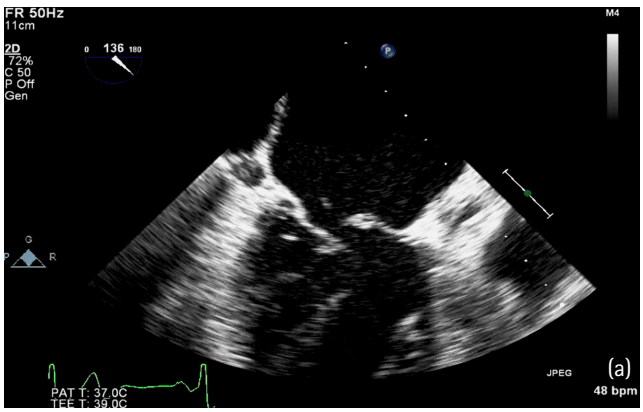
is software available from several manufacturers that allows for 3D quantitative assessment of the MV structure, which has helped elucidate many more details about MV function in both degenerative and especially ischemic MR. Examples are shown in **Figure 1.26**.

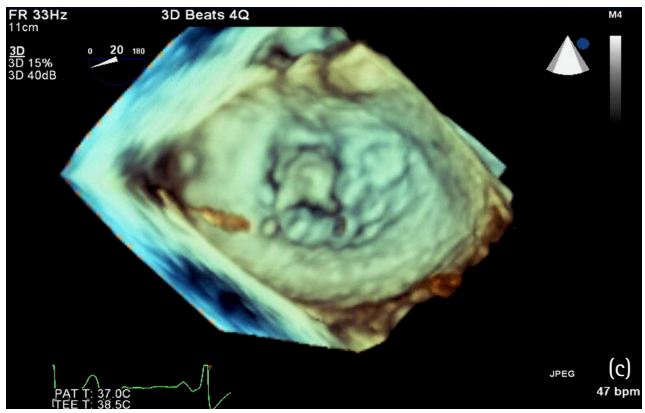
Residual MR after mitral repair is not uncommon. Mild to moderate MR detected under the influence of general anesthetics might revert to severe MR and symptomatic pulmonary edema in the exercising patient. The mechanisms of failed repair include persistent excessive leaflet motion, prolapse, perforation, and a spectrum of disorders producing malcoaptation of the anterior and posterior leaflets.

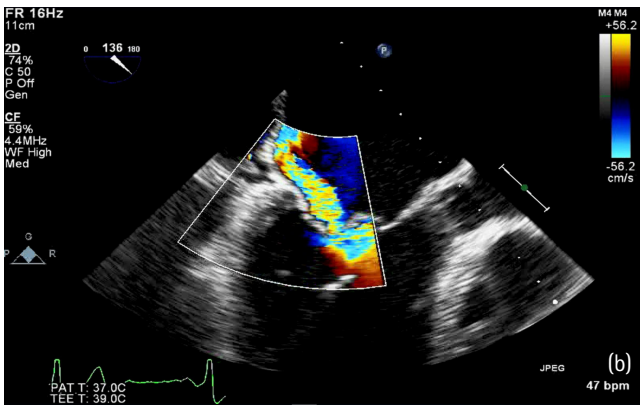
SAM of the MV tends to occur in patients with an excessively long (i.e. edge-to-annulus) posterior leaflet. SAM produces MR and obstruction of the LVOT (**Figure 1.27**). Hypovolemia and vasodilatation exacerbate SAM. Treatment includes volume administration as well as medications to increase afterload and decrease heart rate (i.e. phenylephrine). If persistent, reinitiation of cardiopulmonary bypass and a sliding posterior valvuloplasty or MV replacement may be necessary. The maximum allowable MR after repair is controversial. Many clinicians will accept 1+ MR, especially if reinitiation of cardiopulmonary bypass and recross-clamping poses a significantly increased risk (e.g. elderly, concomitant ischemic disease, decreased EF).

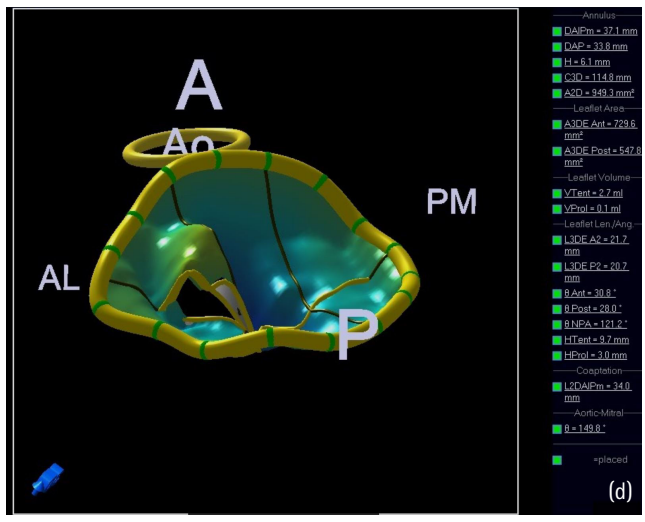


1.27 Systolic anterior motion (SAM) of the mitral valve can produce MR.







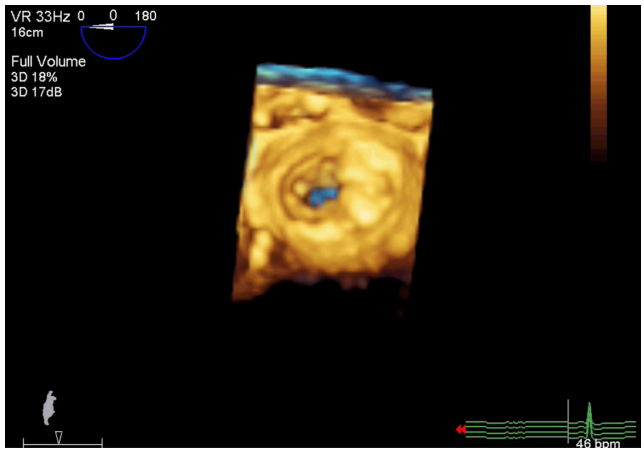


1.26a–d Anterior leaflet (A1) flail in (a) 2D and (b) with color Doppler. (c) 3D TEE of the same lesion and (d) a quantitative map of the MV.

MITRAL STENOSIS

The most common etiologies of mitral stenosis (MS) are rheumatic heart disease and senile calcific disease. As the MV leaflets become increasingly thickened and calcified, their free movement in both diastole and systole becomes limited, resulting in stenosis and often accompanying regurgitation. The decision of when to operate on a patient with MS is determined by the severity of the MS and accompanying symptoms (i.e. LA dilation, arrhythmias, shortness of breath). The severity of MS can be assessed in several ways. The first is by assessment of transvalvular gradients. The obstructed filling of the LV results in an elevated transmitral flow velocity and elevated peak and mean gradients. Mean gradient is used for the grading of MS severity with values of 5–10 mmHg for moderate MS and >10 mmHg for severe MS. PHT can also be used to assess MS severity, with a value of >220 ms corresponding to severe MS and an MV area of <1.0 cm^2.

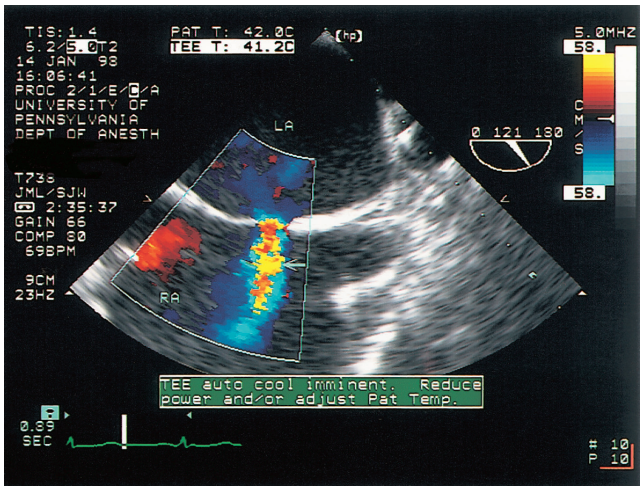
3D TEE can also be beneficial when assessing MS. Aside from being able to better see the movement of the leaflets from both the LA and the LV, MVA can be measured from a 3D data set of a stenotic valve using planimetry with greater accuracy and reproducibility than from 2D echo alone. The reason for this is that the likelihood of a 2D live, TG short-axis view of the MV being perfectly in plane with the minimum valve area is remote while, with 3D TEE, the image can be post-processed so that an en face view of the smallest valve area is easily obtained and measured (**Figure 1.28**).



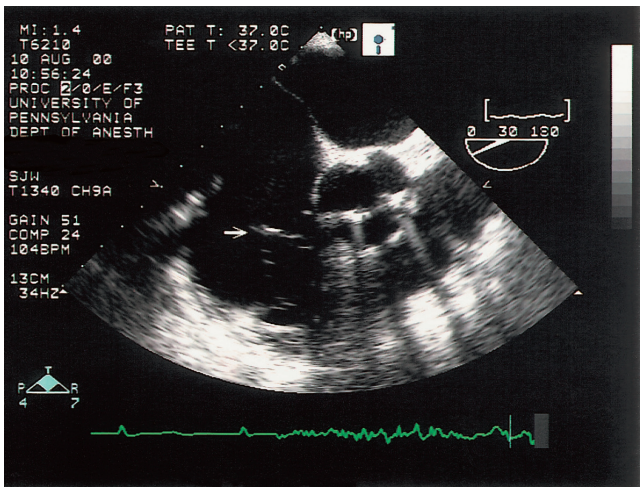
1.28 3D TEE of a stenotic mitral valve.

Tricuspid valve, right atrium, interatrial septum, and pulmonary artery

TEE of the right atrium and tricuspid valve is a reliable method of detecting atrial septal defects, sinus venosus defects, anomalous insertion of pulmonary veins, dilated coronary sinus (i.e. persistent left-sided vena cava), and abnormalities of the tricuspid valve (**Figures 1.29 and 1.30**). Insertion of a coronary sinus cardioplegia cannula can also be facilitated by direct imaging. Patent foramen ovale are common and diagnosis is established using 2D color Doppler and/or contrast echocardiography.



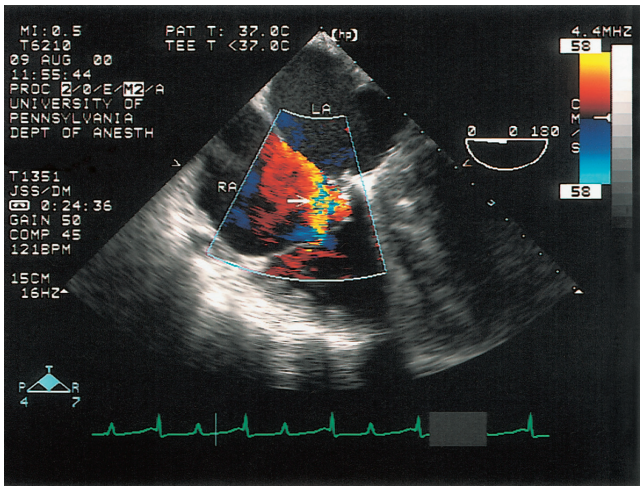
1.29 Midesophageal bicaval view with blood flow through a patent foramen ovale (arrow).



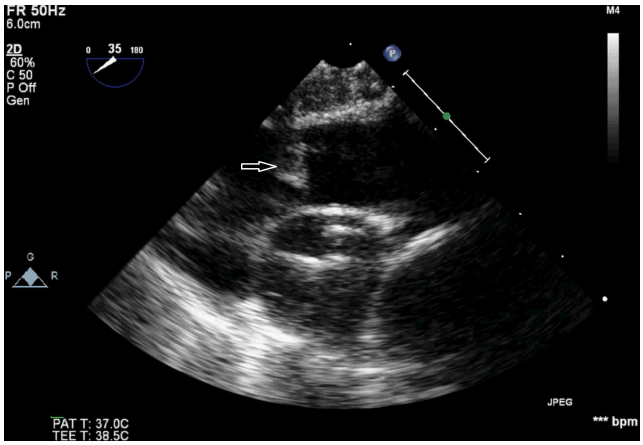
1.30 Midesophageal AV short-axis view. Dilated right atrium with flail portion of tricuspid valve (arrow).

Tricuspid regurgitation (TR) is becoming a more widely recognized problem in cardiac surgery patients (**Figure 1.31**), and severe TR has been shown in some studies to be an independent predictor of mortality. The decision of whether to repair a tricuspid valve during concomitant cardiac surgery is often made in the operating room based upon TEE findings. The severity of TR is based on the size of the regurgitant jet in the right atrium, the vena contracta width of the TR, and the presence or absence of systolic flow reversal in the hepatic veins. Tricuspid valve replacement is much less common than repair and is most frequently due to endocarditis, although damage to the valve from carcinoid heart disease or iatrogenic injury from EP or other procedures is also seen.

TEE views of the main pulmonary artery (PA) include the midesophageal RV inflow–outflow view, the midesophageal ascending aorta SAX view (**Figure 1.32**), and the UE aortic arch SAX view. These allow for the assessment of pulmonary arterial dilation as well as the presence of any large thrombi that may necessitate embolectomy or AngioVac procedure.



1.31 Midesophageal four-chamber view demonstrating moderate tricuspid regurgitation (arrow).



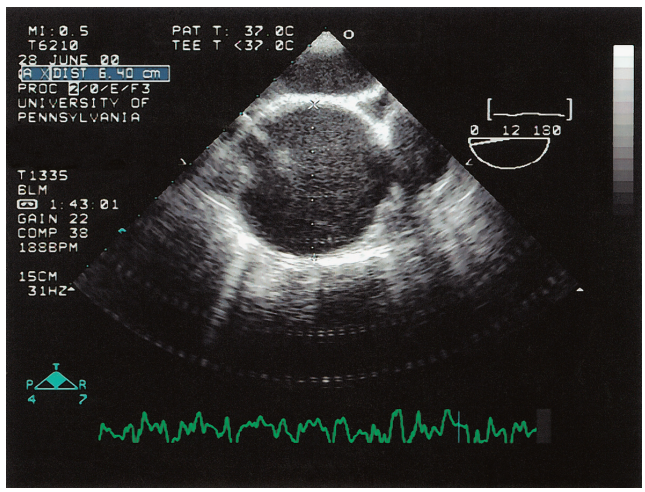
1.32 Mobile thrombus seen in the right main pulmonary artery in the midesophageal ascending aorta short-axis view.

The presence of a large PE is often accompanied by acute RV dilation and failure, and RV free wall akinesis with apical sparing may be seen (McConnell's sign). The pulmonic valve is not always seen clearly with TEE due to its anterior position in the chest, but a basic interrogation for regurgitation and/or stenosis with color Doppler is usually possible. In those patients with pulmonic valve disease, a TTE may provide more information for diagnosis and surgical planning.

Thoracic aorta

AORTIC ANEURYSM

Patients presenting with an aortic aneurysm for elective repair have generally had their diagnosis confirmed by a variety of imaging modalities, including TTE, CT, MRI, and/or angiography before arriving in the operating room. Patients may, however, present for emergent surgery in the setting of rupture or dissection of a known aneurysm. The decision of when to operate on a dilated thoracic aorta depends largely on the diameter of the aneurysm and the rate of expansion, and varies between normal patients and those with a family history of thoracic aortic disease, bicuspid AV, or known collagen vascular disease. The pre-procedure TEE in aortic aneurysm repair should focus on measurement of the aneurysm itself as well as the adjacent normal aortic tissue for graft sizing, interrogation of the AV to determine whether concomitant AVR is necessary, and evaluation of ventricular function (**Figure 1.33**). The post-procedure TEE is aimed at assessing the repair and detecting infrequent complications, like malperfusion, dissection, residual intracavitary air or debris, and worsened AR. New regional wall motion abnormalities may suggest ischemia from air emboli or a technical issue with the anastomosis of the coronary ostia onto the graft if the aortic root was replaced.



1.33 Midesophageal ascending aorta short-axis view demonstrating an aneurysm.

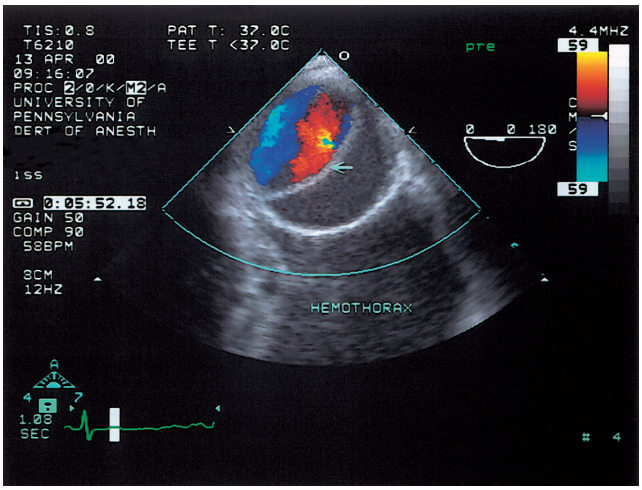
AORTIC DISSECTION

TEE offers several distinct advantages in the diagnosis of an acute aortic dissection. These include a high sensitivity and specificity (98% and 95% respectively according to a meta-analysis by Shiga et al.), expediency, and the ability to simultaneously assess LV function and look for AR or a pericardial effusion. The major disadvantage of TEE when compared to CT or MRI is the inability to image the distal portion of the ascending aorta and proximal arch due to the location of the air-filled trachea, so a dissection isolated to this location may be missed if TEE is the sole imaging modality. Given TEE's utility in aortic dissection, it is common to have patients admitted straight to an operating room from the emergency department or an outside hospital if a dissection is suspected based on history, physical exam, or imaging. Once in the operating room, general anesthesia is carefully induced and a TEE probe is placed, where the diagnosis of aortic dissection can be confirmed and a decision can be made about whether to proceed emergently with surgery or if the patient should be sent to the ICU for medical management and possible eventual open (TAAA repair) or endovascular (TEVAR) repair. The major deciding factor between emergent surgery or the ICU is whether the dissection involves the ascending aorta (Type A) or is isolated to the DTA (Type B). The former is a surgical emergency, while the latter may be managed medically unless there are signs of malperfusion, rupture, or hemodynamic instability. Bypassing the delay and risk associated with obtaining CT or MRI scans, often in isolated, poorly monitored locations, can be life-saving. See **Figures 1.34** and **1.35**.

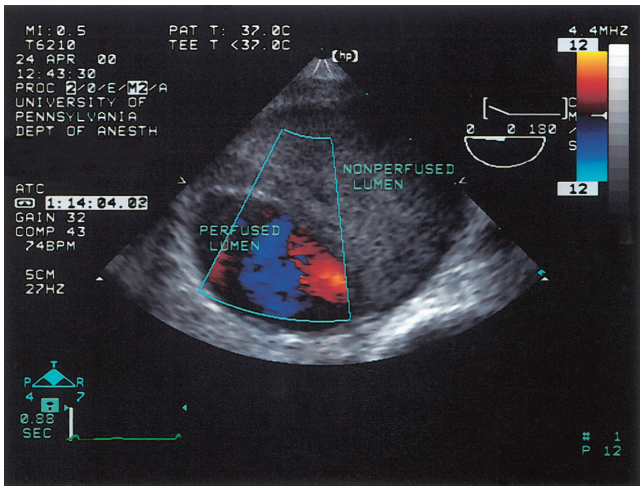
Color-flow Doppler may detect blood flow within a true (endothelial/atherosclerotic lined) and/or false lumen. An entry site (fenestration) between the true and false lumen is often identified. The absence of a discrete flap does not exclude the diagnosis of dissection. Intramural hematoma is never a normal finding and implies significant injury to the integrity of the aortic wall (e.g. dissection, transection, or disruption). Hematoma may appear as an echogenic mass within the media or adjacent to the aorta, contained by echogenic adventitia. Caution should be used to avoid misinterpretation due to ultrasound artifacts such as reverberation artifact and beam-width artifact in oblique image planes. Transthoracic imaging of the suprasternal notch may reveal a limited dissection in the portion of the aortic arch that is not readily accessible by TEE. Ultrasound examination of the carotid arteries may also be useful to detect extension of the dissection into the carotid arteries, as well as confirm bilateral flow post-repair.

Extension of the dissection flap into the aortic root can result in a flail aortic cusp and severe AR or can propagate down one or both coronary ostia, producing severe ventricular dysfunction. Aortic rupture into the pericardium or pleural space is often fatal. However, if the rupture is contained by adjacent structures, a pericardial effusion/tamponade or pleural effusion can be detected and tolerated by the patient until emergency surgery corrects the defect.

Initial echocardiographic assessment should focus on a detailed examination of all parts of the thoracic aorta with and without color Doppler to detect an intimal flap and confirm the diagnosis of aortic dissection. A transgastric short-axis view of the LV determines whether the pericardium contains blood and permits assessment of regional and global ventricular function. The midesophageal AV short-axis and long-axis views provide images of AV integrity and allow the detection of AR as well as measurement of the aortic annulus and root to guide valve repair or replacement if necessary. Color-flow Doppler imaging can be used to verify flow within the proximal right and left coronary arteries. On initiation of cardiopulmonary bypass, the adequacy of arterial inflow into the true lumen should be confirmed, and flow in the carotid arteries can be assessed using a handheld transducer.



1.34 Descending aorta short-axis view. Aortic dissection with pleural effusion, probably hemothorax. The hallmark of aortic dissection is a linear, mobile echogenic density (i.e. intimal flap [arrow]) within the lumen of the aorta. Undulating motion of the flap can be associated with systole.

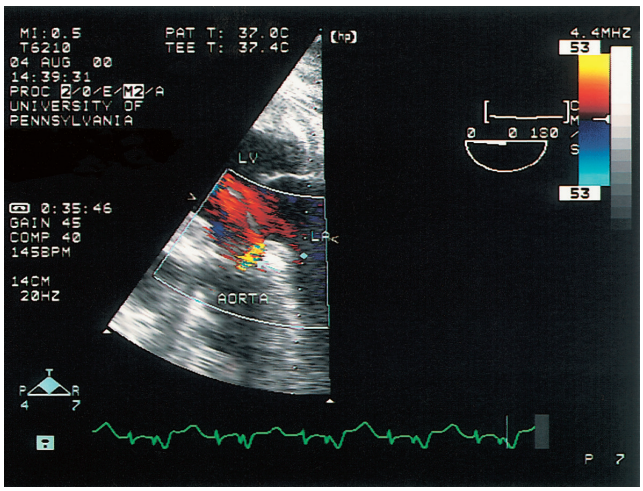


1.35 Descending aorta short-axis view. Aortic dissection with thrombosed false lumen.

Prosthetic valves

The interrogation of a prosthetic valve, either in the setting of a fresh valve replacement or redo surgery, presents a unique set of challenges to the echocardiographer. There are two main types of prosthetic valves, each with their own unique imaging characteristics. Bioprosthetic valves consist of animal-derived leaflet tissue (often bovine or porcine) with a metallic and fabric stent structure and sewing ring (although stentless valves also exist). Mechanical valves are most often bileaflet in construction, but other designs may be seen, especially in older patients. Both valves produce a number of imaging artifacts due to their structure, including shadowing, mirroring, side-lobe artifacts, and others, which can make accurate assessment of function difficult. Mechanical valves also have physiologic washing jets (the number and characteristics of which vary by valve) which can make the detection of paravalvular leaks difficult.

Generally, paravalvular leaks typically produce high-velocity, high-variance jets external to the sewing ring that extend farther into the adjacent cardiac chamber than a typical washing jet. In **Figure 1.36**, a deep transgastric long-axis view demonstrates a paravalvular leak from a prosthetic valve in the aortic position.



1.36 Deep transgastric long-axis view showing a paravalvular leak from a prosthetic valve in the aortic position.

Intravalvular leaks may also be seen in prosthetic valves, and are due to leaflet dysfunction or destruction or impingement of leaflet movement by valve malposition, pannus formation, or some other structure. Prosthetic valve stenosis may be detected via Doppler measurements of transvalvular peak and mean gradients. 3D TEE may be especially useful when assessing for paravalvular leak, as it allows visualization of the entire valve and sewing ring in one image, facilitating rapid localization of the leak and guidance of surgical or transcatheter closure.

FURTHER READING

Andrawes M, Feinman J. 3-dimensional echocardiography and its role in preoperative mitral valve evaluation. *Cardiol Clin.* 2013; 31: 271–85.

Baumgartner H, Hung J, Bermejo J, et al. Echocardiographic assessment of valve stenosis: EAE/ASE recommendations for clinical practice. *J Am Soc Echocardiogr.* 2009; 22: 1–23.

Hahn, RT, Abraham T, Adams MS, et al. Guidelines for performing a comprehensive transesophageal echocardiographic examination: recommendations from the American Society of Echocardiography and the Society of Cardiovascular Anesthesiologists. *J Am Soc Echocardiogr.* 2013; 26: 921–64.

Kallmeyer IJ, Collard CD, Fox JA, et al. The safety of intraoperative transesophageal echocardiography. *Anesth Analg.* 2001; 92: 1126–30.

Lang RM, Badano LP, Mor-Avi V, et al. Recommendations for cardiac chamber quantification in adults: an update from the ASE and EACVI. *J Am Soc Echocardiogr.* 2015; 28: 1–39.

Mathew JP, Swaminathan M, Ayoub CM. *Clinical manual and review of transesophageal echocardiography.* 2nd edn. New York: The McGraw-Hill Companies; 2010.

Shiga T, Wajima Z, Apfel CC, et al. Diagnostic accuracy of transesophageal echocardiography, helical computed tomography, and magnetic resonance imaging for suspected thoracic aortic dissection. *Arch Int Med.* 2006; 166: 1350–6.

Zoghbi WA, Enriquez-Sarano M, Foster E, et al. Recommendations for evaluation of the severity of native valvular regurgitation with two-dimensional Doppler echocardiography. *J Am Soc Echocardiogr.* 2003; 16: 777–802.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Cardiopulmonary bypass: access, technical options, and pathophysiology

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HISTORY

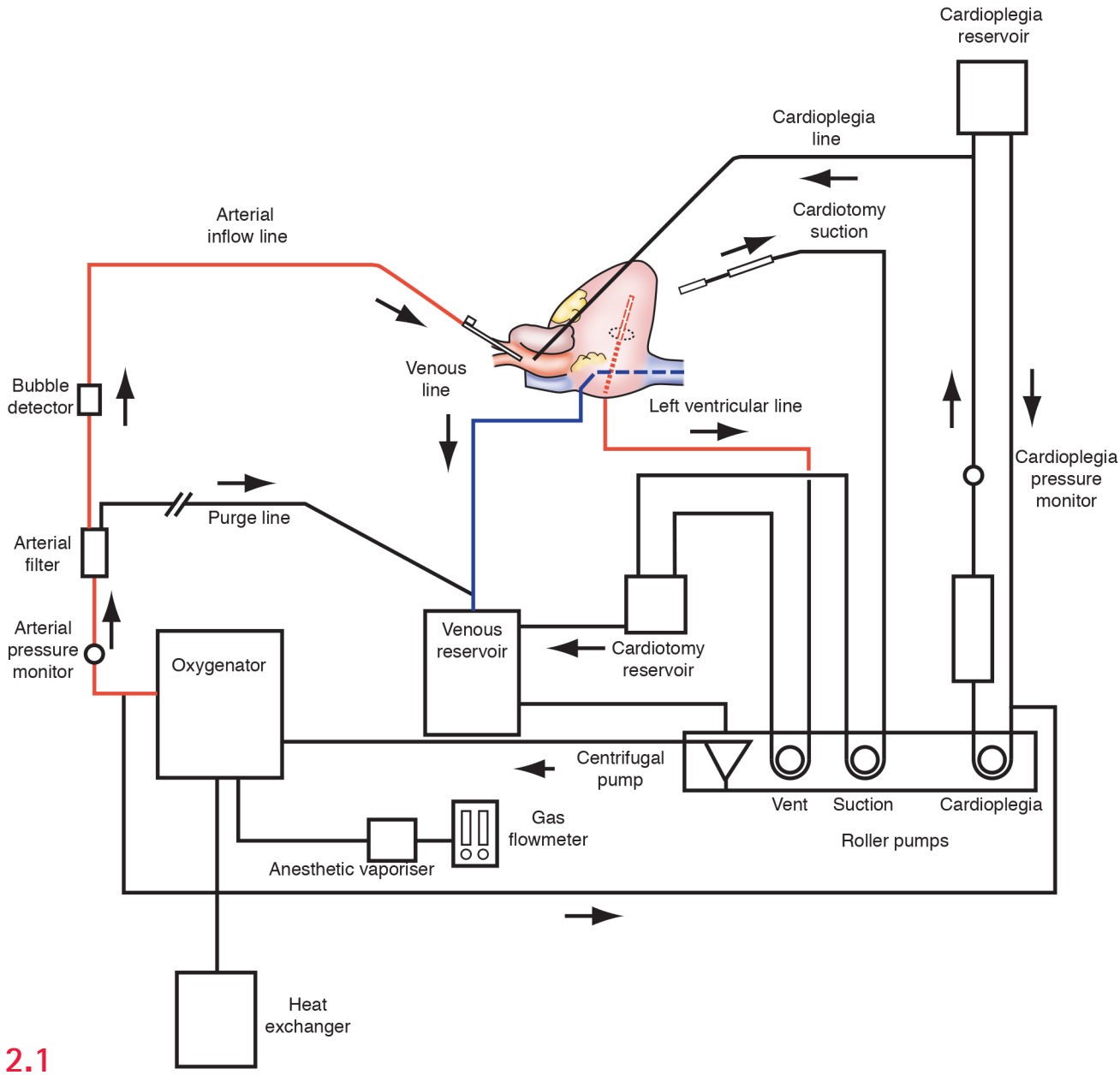
The development of cardiopulmonary bypass (CPB) can be largely attributed to the pioneering work of John Gibbon, who demonstrated its first successful use in animals in the 1930s and performed the first successful human open heart operation in 1953, when he repaired an atrial septal defect using CPB. This initial success was unfortunately followed by several deaths, and he became discouraged by the results and postponed its subsequent human use. At around the same time, C. Walton Lillehei began using controlled cross-circulation from parent to child to allow intracardiac repairs. In 1965, John Kirklin used a modified Gibbon heart–lung machine for intracardiac repair in a series of patients, heralding the era of CPB. Since this early work, progressive developments have occurred in materials used and in surgical techniques to improve the safety, reliability, and efficacy of CPB.

PRINCIPLES AND JUSTIFICATION

CPB is utilized when an empty heart is required for intracardiac repair, when cardiac mechanical arrest is needed, when cardiac manipulation requires circulatory support, and when deep hypothermia is needed to allow for a period of systemic and/or cerebral circulatory arrest. During CPB, systemic deoxygenated venous blood drains into the extracorporeal circuit and passes via a venous reservoir to a pump, which propels blood through a membrane oxygenator for gas exchange before return to the systemic arterial circulation (**Figure 2.1**). This circuit diverts blood flow from the patient's cardiopulmonary circulation while maintaining blood oxygenation and organ perfusion. The circuit also includes a heat exchanger for body temperature manipulation and access ports for the administration of perfusate and drugs and for acquisition of intraoperative blood samples. Additional components of the bypass circuit enable the administration of cardioplegia solution, venting of cardiac chambers, and blood salvage from the surgical field.

Systemic anticoagulation is required during CPB to prevent blood clotting within the circuit. A systemic bolus of 300 units/kg of unfractionated heparin is administered prior to cannulation to maintain an activated clotting time (ACT) of greater than 400 seconds during bypass. The ACT is routinely monitored in 20–30-minute intervals throughout the bypass run, and heparin is readministered to maintain adequate anticoagulation. A fraction of patients exhibits heparin resistance, defined by failure to achieve the ACT goal despite escalated heparin dosing. This process is mediated at least in part by deficiency of antithrombin III and is rectified by administration of either fresh frozen plasma or antithrombin concentrate, which is more expensive but curbs transfusion risks. Patients who are unable to receive heparin (e.g. patients with heparin-induced thrombocytopenia) can safely be anticoagulated with a direct thrombin inhibitor such as bivalirudin or by utilizing a protocol with intravenous epoprostenol in addition to heparin.

Adequate pump flow rates on CPB depend on the temperature and body surface area of the patient. At physiologic temperatures, a minimum of 2.2 L/m^2 should be maintained. The use of therapeutic hypothermia can reduce flow requirements. As a general principle, systemic oxygen consumption decreases about 10–12% for every 2 °C reduction in body temperature. In practice, this concept allows for up to 20–40 minutes of safe circulatory arrest with selective cerebral perfusion and systemic cooling to 24 °C. There is considerable variability in the practice of surgeons regarding optimal temperature management during CPB. Multiple clinical trials have demonstrated that routine cardiac operations can be safely performed under only mild hypothermia without active cooling through the bypass circuit. Rewarming should be timed to allow for normothermia at the end of the bypass run to minimize time on pump.



2.1

While limited data exist on optimal systemic perfusion pressures on bypass, experimental models suggest maintenance of a mean arterial pressure no less than 40 mmHg is sufficient. In practice, maintaining a more physiologic mean pressure of 60 mmHg is a safe approach, and relatively higher pressures should be targeted in the setting of known atherosclerotic cerebrovascular disease. Systemic blood pressure is highly dynamic in the cardiac operating room due to fluid shifts, variable pump flow rates, and the vasodilatory properties of anesthetics. Accordingly, constant communication between the surgeon, anesthesiologist, and perfusionist is necessary to maintain adequate perfusion, minimize blood loss from the extracorporeal circuit, and optimize working operative conditions.

PREOPERATIVE ASSESSMENT AND PREPARATION

In the modern era of cardiac surgery, an expanding array of available cannulation and perfusion strategies enables the surgeon to optimize the operative field for the planned operation. The surgeon must develop a preferred plan as well as contingencies for both suspected and unforeseen

complicating factors. The preoperative assessment for any cardiac case should include consideration of venous and arterial cannulation strategies, the need for venting cannulae, and myocardial protection. The selection of an appropriate arterial cannula is made based on the body surface area of the patient and vascular anatomy. A 20-French aortic cannula is generally sufficient for most adult cardiac operations.

Preoperative history and physical exam should identify history or stigmata of cerebrovascular disease, ventricular dysfunction, renal disease, and peripheral vascular disease. All preoperative imaging should be reviewed, including assessment for calcification of the aorta to ensure safe central cannulation and for atherosclerotic disease that may complicate peripheral cannulation or placement of an intra-aortic balloon pump.

ANESTHESIA

General anesthesia with neuromuscular blockade and endotracheal intubation is required for cardiac surgical cases. If operative strategy dictates thoracotomy with single-lung ventilation, either a dual-lumen tube or bronchial blocker is used for bronchial isolation. Multimodal invasive and external monitoring devices should be routinely employed to guide intraoperative decision-making (**Table 2.1**). At a minimum, surface ECG, pulse oximetry, radial and/or femoral arterial catheters, and a Foley catheter should be in place prior to commencing a cardiac operation. Transesophageal echocardiography is routinely employed. Cerebral near-infrared spectroscopy (NIRS), traditionally used in aortic procedures, should be considered for all cases. A pulmonary artery catheter provides real-time monitoring of hemodynamic parameters but is not necessarily required in all cases.

Table 2.1 Multimodal monitoring

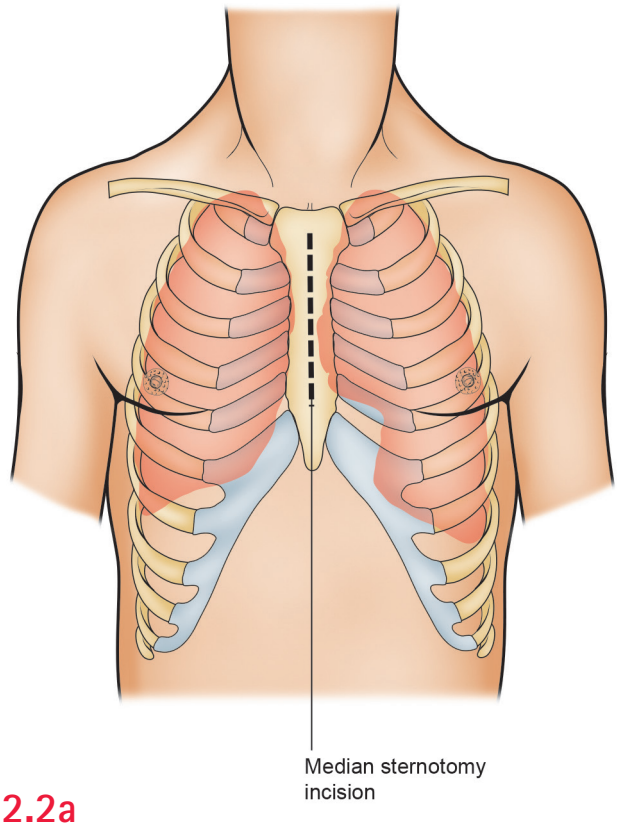
Monitoring modality	Parameters
Surface ECG	Heart rhythm, ischemia
Arterial catheter	Blood pressure, arterial blood gas
Pulmonary artery (Swan–Ganz) catheter	CVP, PA pressure, cardiac output
Transesophageal echocardiology (TEE) probe	Ventricular function, valvular disease, cannula/wire placement
Foley catheter	Core temperature, urine output
Cerebral near-infrared spectroscopy (NIRS)	Cerebral oximetry (oxygenation)

In particularly high-risk cases with elevated concern for cardiovascular collapse during induction of anesthesia (e.g. severe aortic stenosis, critical coronary lesions, severely reduced ejection fraction) the surgeon should consider pre-induction placement of an intra-aortic balloon pump or femoral arterial and venous access to enable rapid cannulation for bypass. Appropriate access for the administration of vasoactive drugs and volume resuscitation generally necessitates large-diameter central venous catheter placement.

OPERATION

Access for central cannulation

Although employment of minimally invasive operations is constantly increasing, most cardiac operations are still performed via median sternotomy (**Figure 2.2a**). Adequate access is feasible through a skin incision starting 3 cm below the sternal notch and ending above the inferior tip of the xiphoid process. For a standard sternotomy, the sternum is completely divided in the midline with a reciprocating sternal saw.



2.2a