Cardiology Procedures

A Clinical Primer

Robert C. Hendel
Carey Kimmelstiel
Editors

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For our trainees – past, present, and future....
Through training and life-long learning, we
impact on those who entrust their care to us
…. And for our colleagues who make our
cloudy days sunny.

R. Hendel and C. Kimmelstiel

To my mentors and family who have guided my
professional career and attempted to instill not only
knowledge but wisdom, and with special gratitude
to my father, Stanley Hendel, whose century
of experience continues to inspire all of those
around him

R. Hendel

To Laurie, Dana and Matt who have always been there
to support me in good and difficult times and to my
parents who every day asked me: "What did you learn
in school today?"

C. Kimmelstiel

Foreword

The last 50 years have witnessed remarkable growth in our understanding of cardiovascular disease. Furthermore, the ability of physicians to diagnose and treat patients with cardiovascular disorders has expanded in step with the enlarging knowledge concerning the pathophysiology of heart and vascular diseases. Effective therapy for patients with these disorders can only occur when an accurate diagnosis has been made. For example, starting in the early 1950s, invasive cardiac diagnostic ability and effective cardiac surgical intervention advanced together. The latter half of the twentieth century and the early years of the twenty-first century have seen explosive growth in our ability to perform accurate and economically appropriate invasive and noninvasive diagnostic evaluations followed by appropriate therapeutic interventions.

In this regard, Drs. Hendel and Kimmelstiel have assembled in this text an impressive array of experts who have clearly and concisely reviewed the essential features of the totality of cardiologic diagnostic and therapeutic procedures. Each chapter concisely describes the indications for the various procedures followed by explicit instructions for preparing patients for the test or intervention described. Subsequent material then succinctly describes the most effective and safe method for carrying out the specific test or intervention. Didactic material is elegantly supplemented by informative case presentations.

This text will be of great value to cardiology trainees and experienced cardiologists who desire a concise and well-illustrated source of information covering cardiac diagnostic and therapeutic procedures. Drs. Hendel and Kimmelstiel are to be congratulated on assembling an outstanding group of experts in the field and for bringing so much useful information together in such a visually and didactically outstanding fashion. I am particularly happy with this outstanding text since I helped train both of the editors during my time at the University of Massachusetts Medical School in Worcester, Massachusetts.

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Chapter 1
Transthoracic Echocardiography

Eddy Karnabi

Echocardiography has become the most widely used imaging procedure in patients with cardiovascular disease. The basis of echocardiography relies on the transmission and reflection of ultrasound waves from a transducer and interaction with different tissue interfaces to generate a digital image. The images obtained include M-Mode, 2D, 3D and Doppler (CW: continuous wave, PW: pulse wave, color and tissue Doppler) to define both normal and abnormal structures and pathologies. The uses include evaluation of the structures of the cardiac chamber walls, the systolic and diastolic performances of the ventricles, the structure and function of the native or prosthetic cardiac valves, evidence of pericardial effusion and constriction, the appearance of the proximal great vessels and inferior vena cava, and the presence of abnormal intracardiac shunting.

Indications

The American College of Cardiology (ACC) and American Heart Association (AHA) published guidelines for the clinical application of echocardiography in 1997 (with an update in 2003) for various cardiovascular conditions [1]. In 2011, the ACCF/ASE/AHA/ASNC/HFSA/HRS/SCAI/SCCM/SCCT/SCMR Appropriate Use Criteria for Echocardiography were published with the level of appropriateness to guide physicians [2]. These of indications are extensive and generally includes usefulness in the acute setting and in patients with cardiac signs and symptoms, patients with valvular heart disease, hypertension, heart failure and cardiomyopathies, cardiac masses and pericardial diseases, suspected cardiovascular sources of emboli, and aortic diseases (Table 1.1).

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Table 1.1 Appropriate indications for transthoracic echocardiography

1.	Symptoms or conditions potentially related to suspected cardiac etiology including but not limited to chest pain, shortness of breath, palpitations, TIA, stroke, or peripheral embolic event
2.	Prior testing that is concerning for heart disease or structural abnormality including but not limited to chest X-ray, baseline scout images for stress echocardiogram, ECG, or cardiac biomarkers
3.	Frequent VPCs or exercise-induced VPCs, Sustained or non-sustained atrial fibrillation, SVT, or VT
4.	Clinical symptoms or signs consistent with a cardiac diagnosis known to cause lightheadedness/presyncope/syncope (including but not limited to aortic stenosis, hypertrophic cardiomyopathy, or HF), Syncope when there are no other symptoms or signs of cardiovascular disease
5.	Evaluation of suspected pulmonary hypertension including evaluation of right ventricular function and estimated pulmonary artery pressure, Routine surveillance (>1 year) of known pulmonary hypertension without change in clinical status or cardiac exam, Re-evaluation of known pulmonary hypertension if change in clinical status or cardiac exam or to guide therapy
6.	Hypotension or hemodynamic instability of uncertain or suspected cardiac etiology
7.	Acute chest pain with suspected MI and non-diagnostic ECG when a resting echocardiogram can be performed during pain, Evaluation of a patient without chest pain but with other features of an ischemic equivalent or laboratory markers indicative of ongoing MI
8.	Suspected complication of myocardial ischemia/infarction, including but not limited to acute mitral regurgitation, ventricular septal defect, free-wall rupture/tamponade, shock, right ventricular involvement, HF, or thrombus
9.	Initial evaluation of ventricular function following ACS, Re-evaluation of ventricular function following ACS during recovery phase when results will guide therapy
10.	Respiratory failure or hypoxemia of uncertain etiology
11.	Known acute pulmonary embolism to guide therapy (e.g., thrombectomy and thrombolytics), Re-evaluation of known pulmonary embolism after thrombolysis or thrombectomy for assessment of change in right ventricular function and/or pulmonary artery pressure
12.	Severe deceleration injury or chest trauma when valve injury, pericardial effusion, or cardiac injuries are possible or suspected
13.	Re-evaluation of known valvular heart disease with a change in clinical status or cardiac exam or to guide therapy
14.	Routine surveillance (>3 years) of mild valvular stenosis without a change in clinical status or cardiac exam, Routine surveillance (>1 year) of moderate or severe valvular stenosis without a change in clinical status or cardiac exam
15.	Routine surveillance (>1 year) of moderate or severe valvular regurgitation without a change in clinical status or cardiac exam
16.	Initial postoperative evaluation of prosthetic valve for establishment of baseline, Routine surveillance (>3 years after valve implantation) of prosthetic valve if no known or suspected valve dysfunction, Evaluation of prosthetic valve with suspected dysfunction or a change in clinical status or cardiac Exam, Re-evaluation of known prosthetic valve dysfunction when it would change management or guide therapy

(continued)

Table 1.1 (continued)

17.	Initial evaluation of suspected infective endocarditis with positive blood cultures or a new murmur, Re-evaluation of infective endocarditis at high risk for progression or complication or with a change in clinical status or cardiac exam
18.	Suspected cardiac mass
19.	Suspected cardiovascular source of embolus
20.	Suspected pericardial conditions, re-evaluation of known pericardial effusion to guide management or therapy
21.	Guidance of percutaneous noncoronary cardiac procedures including but not limited to pericardiocentesis, septal ablation, or right ventricular biopsy
22.	Evaluation of the ascending aorta in the setting of a known or suspected connective tissue disease or genetic condition that predisposes to aortic aneurysm or dissection (e.g., Marfan syndrome), Re-evaluation of known ascending aortic dilation or history of aortic dissection to establish a baseline rate of expansion or when the rate of expansion is excessive, Re-evaluation of known ascending aortic dilation or history of aortic dissection with a change in clinical status or cardiac exam or when findings may alter management or therapy
23.	Initial evaluation of suspected hypertensive heart disease
24.	Initial evaluation of known or suspected HF (systolic or diastolic) based on symptoms, signs, or abnormal test results, Re-evaluation of known HF (systolic or diastolic) with a change in clinical status or cardiac exam without a clear precipitating change in medication or diet, Re-evaluation of known HF (systolic or diastolic) to guide therapy
25.	Initial evaluation or re-evaluation after revascularization and/or optimal medical therapy to determine candidacy for device therapy and/or to determine optimal choice of device
26.	Known implanted pacing device with symptoms possibly due to device complication or suboptimal pacing device settings
27.	To determine candidacy for ventricular assist device, Optimization of ventricular assist device settings, Re-evaluation for signs/symptoms suggestive of ventricular assist device-related complications
28.	Monitoring for rejection in a cardiac transplant recipient
29.	Cardiac structure and function evaluation in a potential heart donor
30.	Re-evaluation of known cardiomyopathy with a change in clinical status or cardiac exam or to guide therapy
31.	Screening evaluation for structure and function in first-degree relatives of a patient with an inherited cardiomyopathy
32.	Baseline and serial re-evaluations in a patient undergoing therapy with cardiotoxic agents
33.	Initial evaluation of known or suspected adult congenital heart disease, Known adult congenital heart disease with a change in clinical status or cardiac exam, Re-evaluation to guide therapy in known adult congenital heart disease

Contraindications

Transthoracic echocardiography has no contraindications, as the use of ultrasound has no adverse effects when used for cardiac imaging. However, ultrasound waves have the potential to cause thermal bioeffects depending on the intensity and length of exposure that are determined by the frequency, focus, power output, depth, perfusion, tissue density; these bioeffects are considered minimal.

Contrast agents, when used, include the following contraindications:

1. Clinical instability with hypotension in such cases as acute myocardial infarction, worsening or clinically unstable heart failure, life threatening ventricular arrhythmias, respiratory failure, severe emphysema, pulmonary embolism;
2. Right-left, bidirectional, or transient right-to-left cardiac shunts;
3. Hypersensitivity to contrast agents.

For additional details about contrast agents, please see Chap. 3 (Contrast echocardiography)

Equipment

The necessary equipment for performing an echocardiographic exam includes the portable echocardiography unit, a suitable ultrasound transducer (typically 2–4 Mhz) and an experienced sonographer or physician. The ultrasound transducer uses a piezoelectric crystal (such as quartz or titanate ceramic) to generate and receive ultrasound waves. The received waves are converted to electrical signals and displayed on the echocardiographic machine. The equipment is portable and allows examination in multiple locations aside from the echocardiography laboratories.

Technique

The echocardiographic examination starts by connecting the ECG electrodes and positioning the patient comfortably in the left lateral decubitus position to obtain optimal images (Obtaining images in supine position are possible if patients are unable to lie on their side). The ultrasound transducer is applied (using a water soluble gel) to the parasternal, apical, subcostal and in some cases suprasternal notch to obtain the usual images of an echocardiographic protocol. Parasternal long axis (PLAX), parasternal short axis (PSAX), apical 4 (A4C), 2 (A2C), and 3-chamber (A3C or long axis), subcostal, and suprasternal notch images are obtained. Doppler echocardiography (color flow, continuous and pulsed wave) is used to determine regurgitant and stenotic flow across valves and measure the velocity, pressure gradients, and volumetric flow. Tissue Doppler (mitral annulus) is used in determining diastolic function.

1. The parasternal long axis view (PLAX) (Fig. 1.1) with the transducer slightly left of the sternum is initiated with the 2D evaluation of a sagittal view of the left ventricle (LV) (long axis view). This view allows evaluation of the structure and systolic function of the LV including LV outflow tract, left atrium (LA), the structure and motion of the aortic valve (AV) right and non-coronary cusps, the proximal aortic size and wall characteristics, and a portion of the right ventricular outflow. The posterior pericardium can also be evaluated for thickening or

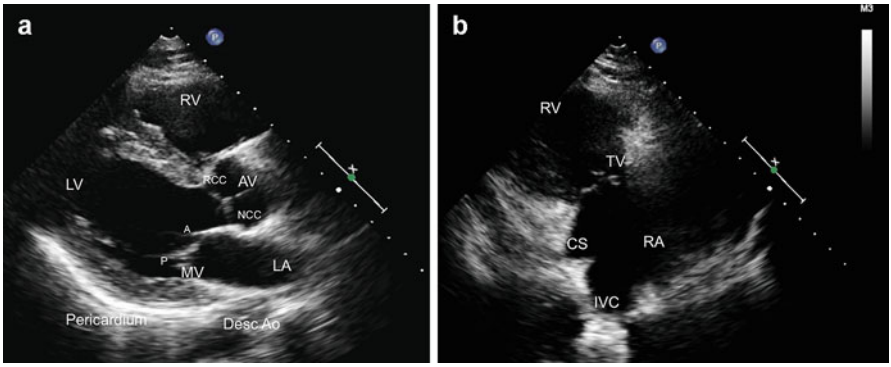

Fig. 1.1 Parasternal long axis (PLAX) views: (**a**) shows PLAX with the LA, LV, MV-mitral valve with anterior and posterior leaflets, AV-aortic valve with RCC-right coronary cusp and NCC-non-coronary cusp. The RV lies anteriorly and posteriorly the pericardium and descending aorta are seen. In the PLAX, the anteroseptal and inferolateral walls of the LV are evaluated for any wall motion abnormalities. Panel (**b**) shows an RV inflow view with the RV, RA, the TV-tricuspid valve as well as the ostia of the IVC-inferior vena cava and the CS-coronary sinus

presence of pericardial effusion and more posteriorly pleural effusion. The septum is visualized and information can be obtained on the presence of a ventricular septal defect (VSD).

2. A parasternal right ventricular (RV) inflow (Fig. 1.1) view can be obtained by medial angulation of the transducer from the parasternal long axis position. This allows visualization of the tricuspid valve (TV), right atrium (RA), coronary sinus (CS), and RV inflow tract. Tricuspid regurgitation can be evaluated and using continuous flow (CW) Doppler, right ventricular systolic pressure (RSVP) can be calculated.
3. Parasternal short axis view (PSAX) (Fig. 1.2) is orthogonal to the long axis view. It is obtained by rotating the transducer 90°. Cross sectional evaluation of the LV, mitral valve (MV), AV, and LA are obtained, as well as views of the interatrial septum, RA, TV, RV outflow tract, PV, proximal PA and main PA branches. Doppler studies allow assessment of aortic regurgitation, tricuspid regurgitation, PA velocity, and the presence of pulmonic stenosis or regurgitation. Shunts that can be assessed in this view include membranous and supracristal VSD, patent ductus arteriosus (PDA), atrial septal defects (ASD) and patent foramen ovale (PFO)
4. Apical four chamber (A4C) view (Fig. 1.3): The transducer is placed on the left side of the chest as far inferiorly and laterally as possible to obtain views of the four chambers, including the mitral and tricuspid valves. This view allows assessment of the LV apex, inferoseptal and anterolateral walls and the lateral RV wall. The view is useful for evaluation of global LV systolic performance and the presence of LV apical aneurysm and thrombus. Diastolic performance can be determined by Doppler assessment of mitral inflow, pulmonary vein, and mitral annular (tissue Doppler) motion. This is the best view for assessing the presence and degree of mitral and tricuspid stenosis and regurgitation and is useful for

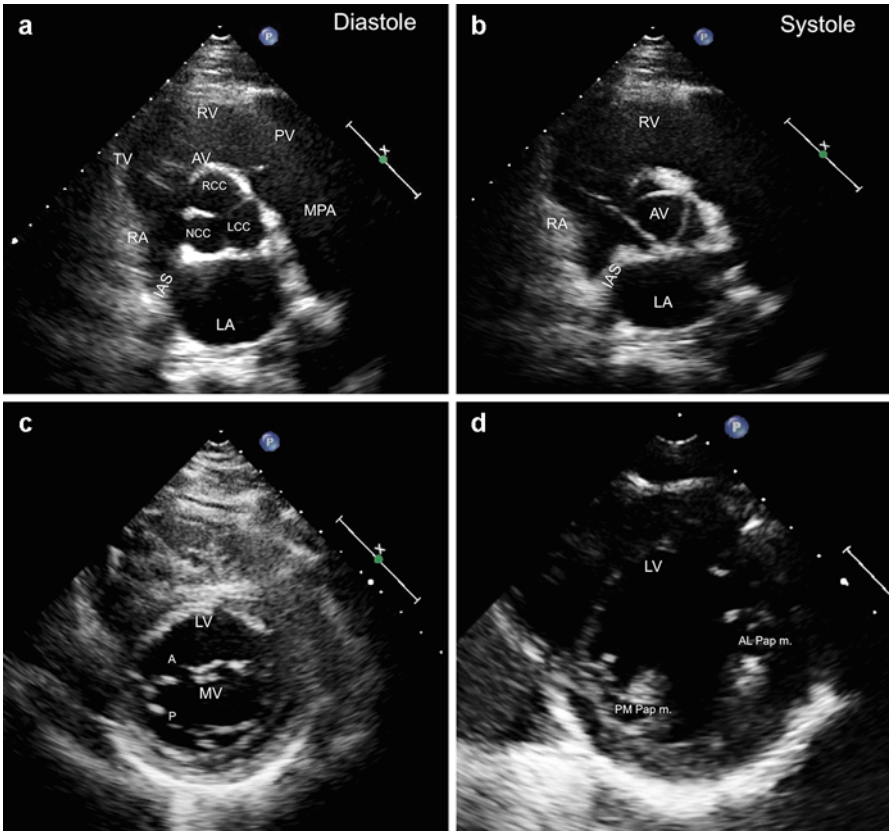

Fig. 1.2 Parasternal short axis (PSAX) views: (**a**, **b**) At the aortic level in diastole (AV closed) and systole (AV open). Note the three cusps: RCC, LCC, and NCC (located at the IAS-interatrial septum). Also seen are the LA, RA, IAS with slight dropout, RV outflow, PV-pulmonary vein and MPA-main pulmonary artery. Panel (**c**) shows short axis of the LV at the mitral valve level showing the anterior and posterior leaflets. Panel (**d**) shows a short axis of the LV at the papillary muscle level with the AL-anterolateral and PM-posteromedial papillary muscles from [1]

assessing the extent of pericardial effusion, and respirophasic characteristics of mitral and tricuspid characteristics that may include pericardial tamponade. RV and RA invagination or compression also suggesting tamponade can be seen in these views. Doppler interrogation for muscular VSD is best accomplished in this view. Saline intravenous injections for R-L shunts are best determined in this view.

5. Apical 2 chamber (A2C) view (Fig. 1.3): Rotation of the transducer 60° counterclockwise provides visualization of the LV, MV, and LA. This view allows evaluation of the LV inferior and anterior walls, further evaluation for mitral regurgitation, and may be the best view for demonstration of LV pseudoaneurysm, which usually involves the inferior wall.
6. Apical 3 chamber (A3C) view (Fig. 1.3): Rotating the transducer 60° clockwise and tilting is slightly anteriorly allows visualization of the LV, MV, LA, LV

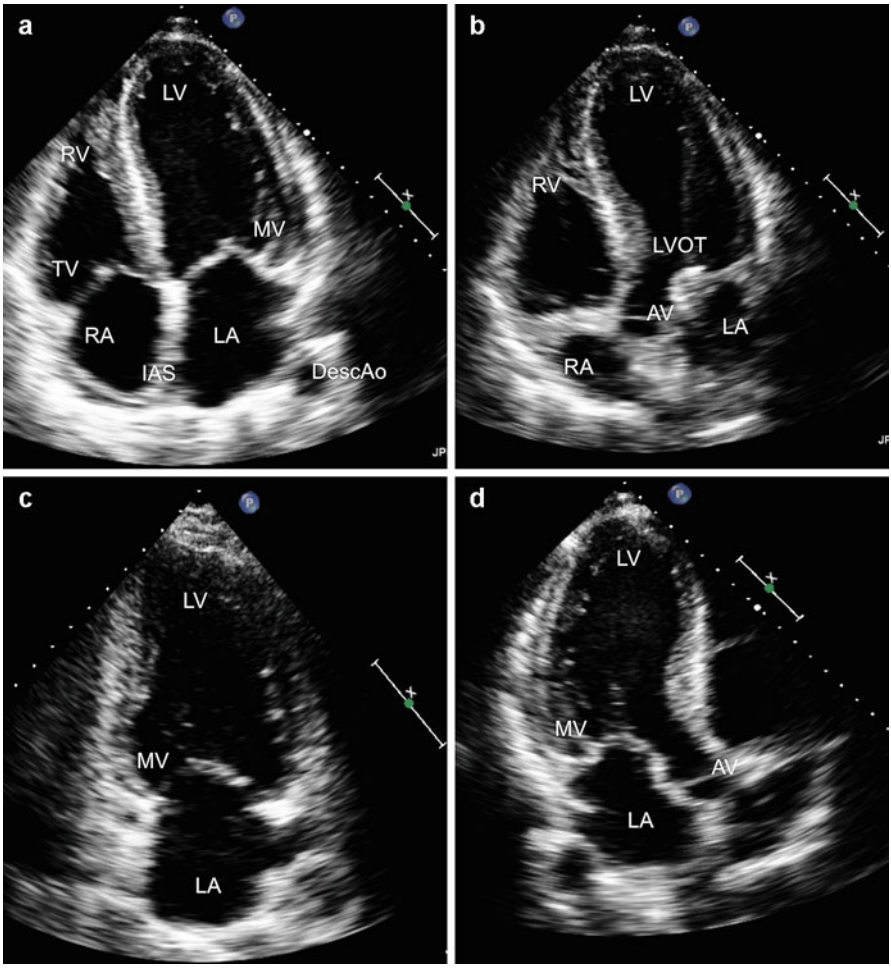

Fig. 1.3 Apical views. (**a**) Apical 4 chamber (A4C) view showing the LA, RA, RV, LV (anterolateral and inferoseptal walls), and the MV/TV. (**b**) Apical 5 chamber (A5C) with slight anterior angulation of the transducer, the aorta is opened and the aortic valve can be seen and interrogated with CW to evaluate for AS, and PW of the LVOT to measure the SV-stroke volume. (**c**) Apical 2 chamber (A2C) showing the LA, MV and LV (Anterior and inferior walls). (**d**) Long axis (A3C) showing the LA, LV, MV, and AV. Similar to the PLAX, the anteroseptal and inferolateral walls of the LV are seen from [5]

outflow tract, AV and proximal aorta. It is the best view for Doppler interrogation for aortic stenosis, subaortic stenosis and aortic regurgitation.

7. Subcostal view (Fig. 1.4): The transducer is placed in the epigastrium just below the subxiphoid process. It is the best view for evaluating RA and RV free wall motion, and presence of PFO or ASD. The inferior vena cava is best viewed in this location. The diameter of which is measured and used to estimate RA pressure. The abdominal aorta can be seen several centimeters below the diaphragm, which allows the evaluation of aneurysms or dissection at this level.

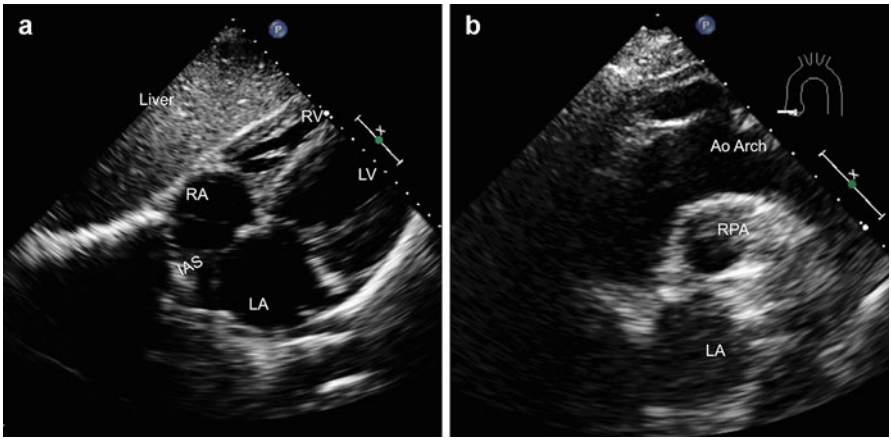

Fig. 1.4 Subcostal and suprasternal TTE views: (**a**) A subcostal view with the four chambers LA, LV, RA, and RV are seen. This is the best view to evaluate for the presence of IAS-interatrial septal defects such as ASDs or PFOs using color flow Doppler. (**b**) Suprasternal notch view showing the aortic arch, RPA-right pulmonary artery and LA. This view is used to evaluate for the presence of aortic coarctation and diastolic flow reversal to determine the severity of aortic regurgitation

8. Suprasternal view (Fig. 1.4): This view allows Doppler assessment of the ascending aortic velocities in aortic stenosis an can provide 2D imaging of the transverse and proximal descending thoracic aorta. Doppler assessment of the descending aorta in this view may be useful for the diagnosis of PDA and coarctation.

In general, standard images can be obtained in most patients with limitations in those with extremes of weight, with severe lung hyperinflation (i.e. severe COPD), or in patients in which access to the chest wall is precluded in setting of thoracic bone malformations, open-heart surgery or other thoracic surgeries. In difficult to image patients, ultrasound contrast agents are used to improve image quality.

Data Interpretation

Physicians with specialized training should perform data interpretation as established by competency guidelines from the ACC/AHA/ASE to generate a formal report. It is important to use a consistent systemic approach with special attention directed to the clinical question.

A systemic approach includes the following:

Left Ventricle: Chamber dimension, wall thickness, fractional shortening (FS), ejection fraction, regional wall motion abnormalities, stroke volume, diastolic characteristics and presence of VSD [3].

Right Ventricle: Chamber dimension, wall thickness and global function.
Left atrium: size, presence of masses or cor triatriatum.
Right atrium: Size, abnormal motion suggesting pericardial tamponade.
Proximal aorta: size, evidence of dissection and fibrocalcific changes.
Proximal PA: size, presence of PDA.
Valves: Stenosis, regurgitation, vegetations, calcification, prolapse, bicuspid and other AV abnormalities.
Congenital anomalies: PFO, ASD, VSD, cor triatriatum, Ebstein anomaly, transposition of ventricles and other congenital abnormalities.
Pericardium: Pericardial effusion, tamponade, constriction.
Hemodynamic: Hemodynamics play an important role in echocardiography and is helpful in evaluating the degree of right to left or left to right shunting, degree of mitral and aortic stenosis, regurgitant flow, PA systolic pressure.

Flows can be calculated using the formula Flow Rate = Area (πr^2) × Vmax. πr^2 represents the area across a circle assuming the left ventricular outflow tract (LVOT) is circular in shape. The volume is calculated as Volume = Area (πr^2) × VTI (Velocity time integral: measured by tracing the CW or PW signal). The stroke volume (SV) can be calculated using multiple methods, with the use of the LVOT being the most accurate: SV = Area (LVOT) × VTI (PW LVOT). The SV can also be calculated by SV = EDV − ESV by tracing the LV in end diastole and end systole and using the biplane summation method to calculate volumes.

The pressure gradients across valves can be calculated using the Bernoulli equation $\Delta p = 4\ V^2$. Another method to evaluate aortic stenosis is by measuring the mean pressure gradient (PG) by tracing the CW AV signal or approximating it by calculating 2/3 or 0.7 of max PG. The aortic valve area (AVA) is calculated using Newton's 2nd law of conservation of energy (Flow in = flow out), therefore, AVA × VTI = CSA (LVOT) × VTI (PW at LVOT). CSA of LVOT = πr^2. R = radius of the LVOT, CSA = Cross sectional area, VTI = Velocity time integral. Lastly, a dimensionless index defined as DVI = VTI (LVOT) divided by VTI (AV) is used to estimate severity with a value less than 0.25 signifying severe. This method avoids the error of measuring the LVOT diameter because LVOT squared- results in squaring any error obtained.

Table 1.2 shows the classification of the severity of aortic stenosis.

Mitral stenosis can be evaluated with several methods including the determination of the mean pressure gradient by tracing the CW signal across the mitral valve

Table 1.2 Recommendations for classification of AS severity [4]

	Aortic sclerosis	Mild	Moderate	Severe
Aortic jet velocity (m/s)	<2.5	2.6–2.9	3.0–4.0	>4.0
Mean PG (mm Hg)	–	<20	20–40	>40
AVA (cm^2)	–	>1.5	1.0–1.5	<1.0
Indexed AVA (cm^2/m^2)	–	>0.85	0.60–0.85	<0.6
Velocity ratio	–	>0.50	0.25–0.50	<0.25

PG pressure gradient, *AVA* aortic valve area

Table 1.3 Recommendations for classification of MS severity [4]

	Mild	Moderate	Severe
Valve area MVA	>1.5	1.0–1.5	<1.0
Mean PG (mm Hg)	<5	5–10	>10
PA pressure (mm Hg)	<30	30–50	>50

The above recommendations are based on the ASE guidelines, however, the AHA/ACC most recent guidelines; define an area >1.5 as progressive, <1.5 as severe, and an area <1.0 as very severe

MVA mitral valve area, *PG* pressure gradient, *PA* pulmonary artery

or by calculating the mitral valve area (MVA) by planimetry using the parasternal short axis at the mitral valve level. Additionally, MVA may also be determined by pressure half time (PHT), which is defined as the time for the LA to LV pressure gradient to fall to half its peak. A deceleration time (DT) can be calculated from the slope and PHT = 0.29 × DT and MVA = 220/PHT (Table 1.3).

Quantification of valvular regurgitation can be achieved using volumetric methods or PISA. The volumetric methods, uses the principle of "What goes in, must come out". Therefore, the regurgitant volume (RV) across the MV RV (MR) = SV (MV) – SV (LVOT) and RV (AI) = SV (LVOT) – SV (MR). The ERO (Effective regurgitant orifice) can be calculated by dividing the regurgitant volume (RV) by the VTI of the regurgitant valve (MR or AI). The regurgitant fraction is calculate by dividing the RV by the SV at the valve i.e., if MR then SV of MV and if AI then SV LVOT. Using the PISA method, by adjusting the aliasing velocity and creating a hemisphere of isovelocity, calculations can be made to quantify regurgitation with the ERO measuring lesion severity and RV measuring volume overload from the regurgitation. ERO = $2\pi r^2$ × Va (Aliasing velocity)/Vmax of MR, RV = ERO × MR VTI, and RF = RV/SV of mitral valve. Similar calculations are made for aortic regurgitation. Tables 1.4 and 1.5 demonstrate the ASE criteria for classification of mitral and aortic regurgitation.

The RVSP and PASP can be estimated. The right atrial pressure (RAP) is estimated using the size or diameter of the IVC. If the IVC diameter is <2.1 cm, the RAP is given a value of 3 mmHg. If the IVC diameter is >2.1 cm and collapses with a sniff or <2.1 cm and is non-collapsed, then a value of 8 mmHg is given. If the IVC is >2.1 cm and is non-collapsed, then a value of 15 mmHg is given. The RVSP can be calculated using the TR velocity by applying the Bernoulli equation with RVSP = 4 V^2 (TR) + RAP. The pulmonary artery systolic pressure (PASP) is estimated to be equal to the RVSP unless pulmonary stenosis is present.

Finally, shunts such as ASD and VSD can be estimated using the Qp/Qs ratio. The formula to calculate the shunt is Qp/Qs = RVOT CSA × RVOT VTI/LVOT CSA × LVOT VTI.

The assessment of diastolic dysfunction is an integral part of a routine echocardiographic examination especially in heart failure patients [6]. Assessment of diastolic dysfunction usually includes measurement of mitral inflow and peak early filling (E-wave) and late diastolic filling (A-wave) velocities, E/A ratio, deceleration time (DT) of early filling velocity and the IVRT (isovolemic relaxation time). Pulmonary venous flow is performed with a PW Doppler at the right upper pulmonary vein. Measurements include peak systolic (S) velocity, peak antegrade

Table 1.4 Qualitative and quantitative parameters in grading mitral regurgitation severity [5]

	Mild	Moderate	Severe
LA and LV size	Normal	Normal or dilated	Usually dilated
Color flow jet area	Small, central jet	Variable	Large jet (>10 cm^2 or >40 % of LA)
Mitral inflow-PW	A wave dominant	Variable	E wave dominant
Jet density-CW	Faint	Dense	Dense
Jet contour-CW	Parabolic	Usually parabolic	Early peaking-triangular
Pulmonary vein flow	Systolic dominance	Systolic blunting	Systolic flow reversal
VC width (cm)	<0.3	0.3–0.69	>0.7
RV (ml)	<30	30–59	>60
RF (%)	<30	30–49	>50
EROA (cm^2)	<0.2	0.2–0.39	>0.4

LA left atrium, *LV* left ventricle, *PW* pulse wave, *CW* continuous wave, *VC* vena contracta, *RV* regurgitant volume, *RF* regurgitant fraction, *EROA* effective regurgitant orifice area

Table 1.5 Qualitative and quantitative parameters in grading aortic regurgitation severity [5]

	Mild	Moderate	Severe
LA and LV size	Normal	Normal or dilated	Usually dilated
Jet width in LVOT-color flow	Small, central jet	Intermediate	Large jet
Jet density-CW	Faint	Dense	Dense
Jet deceleration rate-CW (PHT, ms)	>500	500–200	<200
Diastolic flow reversal in descending aorta-PW	Brief early diastolic reversal	Intermediate	Prominent holodiastolic reversal
VC width (cm)	<0.3	0.3–0.6	>0.6
Jet width/LVOT width, %	<25	25–64	>65
Jet CSA/LVOT CSA, %	<5	5–59	>60
RV (ml)	<30	30–59	>60
RF (%)	<30	30–49	>50
EROA (cm^2)	<0.1	0.1–0.29	>0.3

LA left atrium, *LV* left ventricle, *LVOT* left ventricular outflow tract, *PHT* pressure half time, *PW* pulse wave, *CW* continuous wave, *VC* vena contracta, *RV* regurgitant volume, *RF* regurgitant fraction, *EROA* effective regurgitant orifice area

diastolic (D) velocity, S/D ratio, and the peak A reversal in late diastole. The time difference between it and the mitral A wave duration (Ar-A) is used in assessing diastolic dysfunction. PW tissue Doppler of the septal and lateral mitral annulus is performed in the A4C. The early diastolic annular velocity e′ is integral in the assessment of diastolic function. Normal diastolic function is defined by a septal e′ >8 and lateral e′ >10. If the values are <8 and <10 respectively, multiple parameters are evaluated (E/A, DT, Ar-A, Valsalva ΔE/A) to determine the grade of diastolic dysfunction I, II, or III.

Complications

As mentioned, echocardiography is generally very safe with no complications. The key procedural complications are usually related to contrast administration or inaccuracy of data.

Clinical Vignettes

Case 1

Sixty-five-year-old male with history of hypertension, hyperlipidemia and heavy alcohol and tobacco use was admitted with 2 weeks of worsening dyspnea on exertion, orthopnea and cough with clear sputum production. His vitals include a blood pressure (BP) of 80/44, heart rate (HR) 126 and respiratory rate (RR) of 22. Physical exam is significant for distant heart sounds, few crackles and lower extremity edema. ECG is remarkable for low voltage and electrical alternans. 2D transthoracic images are shown in (Fig. 1.5).

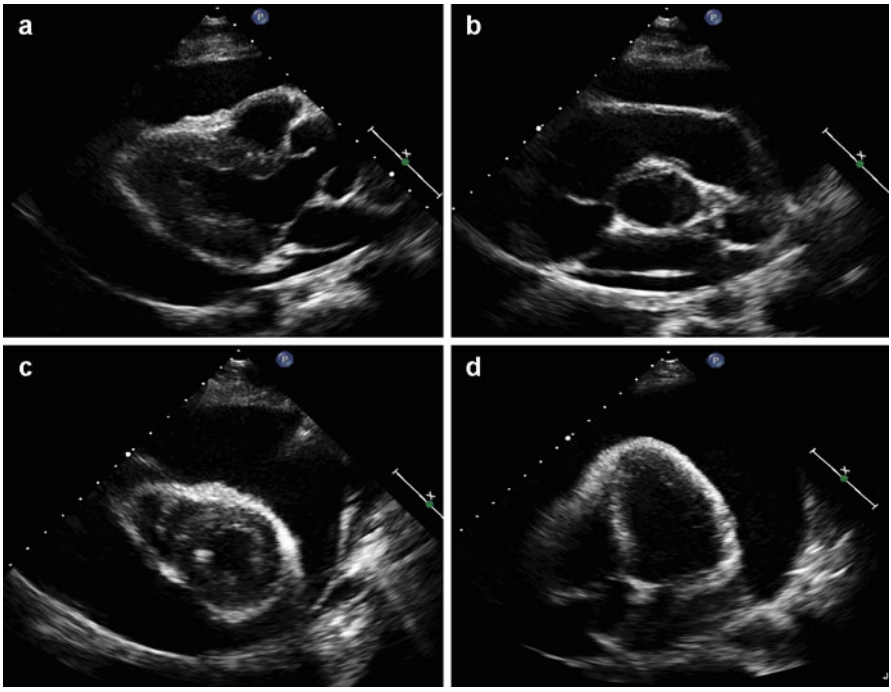

Fig. 1.5 Case #1. (**a**) Parasternal long axis; (**b**, **c**) Short axis, (**d**). Four chamber view (see text for details)

The TTE images clearly show a large circumferential pericardial effusion that is causing hemodynamic compromise and tamponade. Pericardial effusions are classified as small (less than 1 cm), moderate (1–2 cm), and large (>2 cm). In this case, the effusion is 3–4 cm with diastolic collapse or invagination of the right-sided chambers. The treatment of choice is emergent pericardiocentesis.

Case 2

Eighty-five year old male with hypertension, hyperlipidemia, prostate cancer s/p radiation and surgery presented with worsening clinical status over the last year with episodes of chest pain, dyspnea and an episode of syncope that prompt the admission. His Vitals are stable. Physical examination is notable for a grade 3/6 systolic murmur at the right upper sternal border with radiation to the carotids, S2 is diminished, lungs bibasilar crackles. ECG unremarkable. Transthoracic echocardiographic images are shown in (Fig. 1.6).

The TTE images show severe calcifications of the aortic valve with a slit like opening during systole indicating the presence of severe aortic stenosis (As shown in the upper panels). The lower panels show a continuous wave through the aortic valve, a pulse wave at the LVOT level, and a CW of the aortic regurgitation $\Delta p = 4(4\ m/s)^2$ is 64 mmHg. The mean PG is calculated by tracing the CW across the aortic valve or 2/3 of the Peak PG. AVA is calculated at 0.9 cm^2 indicative of severe AS per guidelines (AVA < 1 cm^2) and in symptomatic patients should be referred for aortic valve replacement.

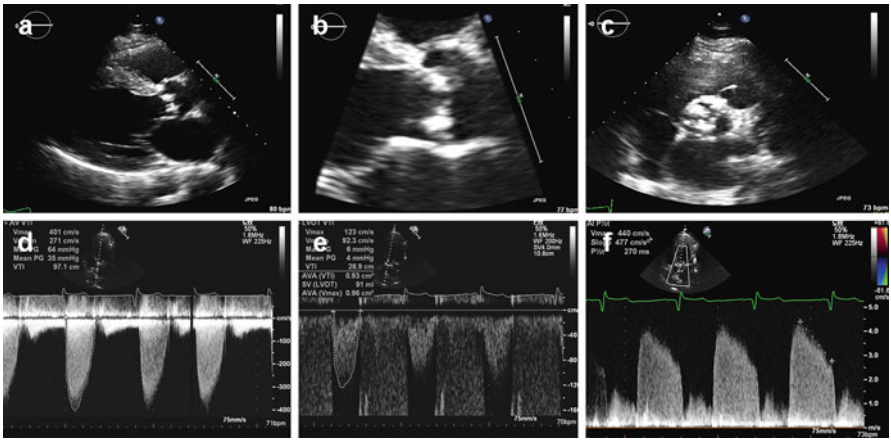

Fig. 1.6 (**a**) Parasternal long axis (severe calcification of the aortic valve) (**b**) zoom on aortic valve (**c**) Parasternal short axis (**d**) Continuous wave Doppler through the aortic valve to measure the peak and mean aortic stenosis gradients. (**e**) Pulse wave Doppler at the LVOT to calculate the aortic stroke volume. (**f**) Continuous wave Doppler through the aortic valve to quantify the pressure half time of aortic regurgitation

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Chapter 2
Transesophageal Echocardiography

Eddy Karnabi

Transesophageal echocardiography (TEE), in comparison to transthoracic echocardiography (TTE), provides superior image resolution/quality and has become the test of choice in many circumstances. Improved image quality is due to the decreased distance and the absence of bone or lung between the transducer and the heart. However, it is an invasive procedure and hence, should be reserved for indications where TTE provides inadequate diagnostic information.

Indications

The most common indications for TEE are as follows: detection of a cardiac source of embolism as in atrial fibrillation or stroke; evaluating the left atrial appendage (LAA) for a thrombus; endocarditis (vegetations) and its complications; valvular disorders especially the mitral and prosthetic valves, diagnosing atrial septal defects (ASD) and patent foramen ovale (PFO); evaluating the thoracic aorta (dissection) and intracardiac masses/tumors. Table 2.1 shows a list of the appropriate indications of TEE based on the ACCF/ASE/AHA/ASNC/HFSA/HRS/SCAI/SCCM/SCCT/SCMR Appropriate Use Criteria [1]:

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Table 2.1 Indications for transesophageal echocardiography [2, 3]

1.	Use of TEE when there is a high likelihood of a nondiagnostic TTE due to patient characteristics or inadequate visualization of relevant structures
2.	Evaluation for cardiovascular source of embolus with no identified noncardiac source
3.	To diagnose infective endocarditis with a moderate or high pretest probability (e.g., staph bacteremia, fungemia, prosthetic heart valve, or intracardiac device)
4.	Evaluation of valvular structure and function to assess suitability for, and assist in planning of, an intervention
5.	Guidance during percutaneous noncoronary cardiac interventions including but not limited to closure device placement, radiofrequency ablation, and percutaneous valve procedures
6.	Suspected acute aortic pathology including but not limited to dissection/transsection
7.	Re-evaluation of prior TEE finding for interval change (e.g., resolution of thrombus after anticoagulation, resolution of vegetation after antibiotic therapy) when a change in therapy is anticipated
8.	Evaluation to facilitate clinical decision making with regards to anticoagulation, cardioversion, and/or radiofrequency ablation

Contraindications

Absolute contraindications	Relative contraindications
Perforated viscous	Restricted cervical mobility such as atlantoaxial joint disease
Esophageal pathology (stricture, tumor, diverticulum, scleroderma, Mallory-Weiss tear)	Recent upper GI bleeding
Active upper GI bleeding	History of GI surgery
Recent upper GI surgery	Esophagitis, peptic ulcer disease
Esophagectomy	Barrett's esophagitis
	History of dysphagia
	Prior radiation to the chest
	Coagulopathy, thrombocytopenia
	Thoracoabdominal aneurysm
	Symptomatic hiatal hernia

Equipment

Similar to a TTE, the necessary equipment's are the portable echocardiography unit; an ultrasound probe with multiplane imaging capabilities and trained personnel in sedation and transesophageal echocardiography based on the ACC/AHA competency guidelines. The TEE probe is a modified gastroesophageal probe with

a 3–7 Mhz ultrasound transducer at its tip. The diameter of an adult transducer is 9–14 mm and can be maneuvered in a left-right direction and retroflexion/anteflexion using a rotating knob/wheel at the proximal operator end. The transducer tip is equipped with a multiplane that can be rotated from 0° to 180°.

The TEE room should be equipped with vitals monitor to record BP, HR, pulse oximeter, oxygen supply, oral suction, bite guard, pillow wedge to position the patient, and a cardiopulmonary resuscitation crash cart.

In addition to the physician, at least two additional personnel are required: a sonographer to operate the echocardiographic machine, optimize and acquire the images, and a nurse that will be monitoring the patient vitals (BP, HR, RR, oxygen saturation), administering sedatives/analgesics, and suctioning the oropharynx.

Technique

The procedure starts with patient and room preparation. The room should be equipped with all the supplies/medications required as indicated above. TEE is considered a semi-invasive procedure and a thorough conversation should be performed with the patient explaining the indications, alternatives and possible complications; informed consent should then be obtained. To avoid or reduce the risk of aspiration, the patient should be NPO for at least 6 h. Prior to the start of the procedure, a review of the patients' history, medications, allergies and laboratory data should be performed. A physical exam should also be performed with attention made to the respiratory, cardiovascular system and the Mallampati score (Class I–IV) (Also see Chap. 17). The physical status classification according to the American Society of Anesthesiologists (ASA) should be performed, Classes I–VI, with a level of III and above requiring anesthesiology support. A recent coagulation profile should be reviewed and if patients are on anticoagulation, those agents should be held hours or days prior depending on the type of agent.

The patient is positioned in left lateral decubitus position at a 30–45° inclination to reduce the risk of aspiration. Local anesthesia spray is then performed using tongue depressors to anesthesize the oropharynx. A bite guard is placed to protect the TEE probe from inadvertent biting. Two techniques have been described for the esophageal intubation: hands-in or hands-out techniques. Using the hands-in technique, two fingers are placed inside the oropharynx and are used to depress the tongue and guide the probe (transducer ultrasound facing towards the tongue) towards the posterior pharynx. If patient is under conscious sedation, he/she can be asked to swallow which assists the probe to easily intubate the esophagus. If resistance is encountered at any point, the probe should not be forced further. The probe has markings to help with localization (distance from incisors to mid esophagus

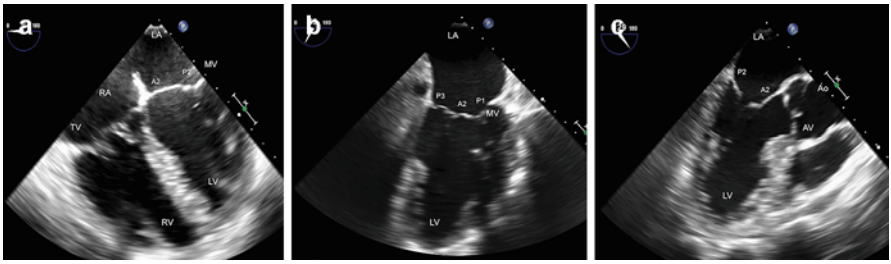

Fig. 2.1 ME (Mid esophageal) TEE images: (**a**) 4 chamber view (0–10°) showing the LA, LV, RA, RV with the mitral and tricuspid valve. Note that the mitral valve is divided into anterior (A1–3) and posterior scallops (P1–3). In this view, A2 and P2 are seen. (**b**) 2 chamber view (50–70°) showing the LA and LV with the mitral valves and P1, A2, and P3 scallops. (**c**) 3 chamber view or long axis (120–140°) showing the LA, LV, mitral valve (A2, P2 scallops) and the aorta with the aortic valve

approx. 30–35 cm and distance to the stomach 40–45 cm). Throughout the procedure, the vital signs should be monitored and the oropharynx suctioned as necessary.

A comprehensive TEE examination is then performed to answer the indication of the study as described below in data interpretation. A key to performing a TEE examination is understanding the terminology of probe manipulation: advancing or withdrawing the probe, flex to the right or left, and anteflexing anteriorly or retroflexing posteriorly. Once the procedure is done, the probe is removed and sent for proper cleaning and the patient monitored for at least 2 h NPO until the gag reflex has returned and the patient recovered from the sedation. If the procedure is elective/outpatient study, he/she is suitable for discharge under the care of a responsible adult with avoidance of driving for at least 12 h.

Data Interpretation

According to the American Society of Echocardiography (ASE), a comprehensive TEE examination includes 28 views. The three primary positions used are upper esophageal (UE), midesophageal (ME), and transgastric (TG). At the ME level, a 5 chamber (5C) at transducer angle 0–10°, 4C at angle 0–10° slight retroflexion, 2C angle 50–70°, and 3C or long axis views at an angle of 120–140° are obtained (Fig. 2.1). At the UE level, a transducer angle of 25–45° will show the aortic valve in short axis, 50–70° shows the pulmonic valve, 90–110° shows the bicaval view and the interatrial septum (Fig. 2.2). The left atrial appendage (LAA) is usually seen at an angle of 60° with slight counterclockwise rotation (Fig. 2.2). In the TG views, a transducer angle of 0–20° will show the LV in short axis at the mitral valve and papillary levels, an angle of 90° shows the LV, mitral valve, and papillary muscles in long axis (Fig. 2.3). Clockwise rotation of the probe will reveal the right side including the RV and the tricuspid valve (Fig. 2.3). In cases of aortic stenosis, the

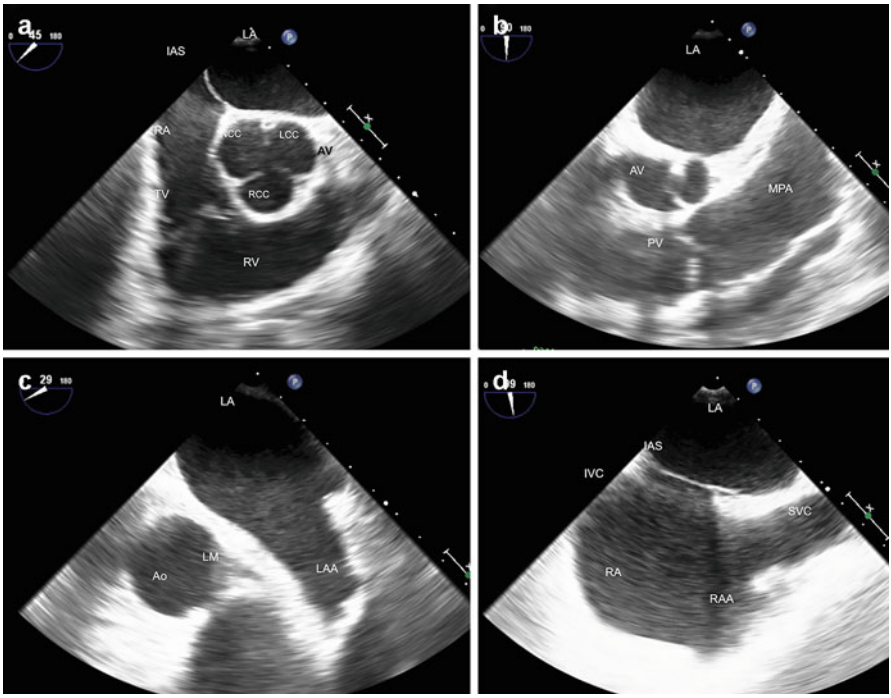

Fig. 2.2 UE (Upper Esophageal) TEE images: (**a**) Short axis of the aortic valve 25–45° showing a tricuspid aortic valve with non-coronary cusp-NCC (at the interatrial septum-IAS), LCC-left coronary cusp, and RCC-right coronary cusp. Note the LA is most posterior and closer to the probe. IAS-inter atrial septum is seen separating the LA and RA. TV-tricuspid valve and the RV outflow tract. (**b**) The PV-pulmonary valve and MPA-main pulmonary arteries are seen with slight increase in the multiplane to 50–70°. (**c**) The probe is withdrawn slightly to above the aortic valve level where the LAA-left atrial appendage can be seen with pectinate muscles at its apex. (**d**) A bicaval view is shown at 90–110° with clockwise rotation with the IAS-interatrial septum, foramen ovale, and RAA-right atrial appendage. Note the location of SVC-superior vena cava and IVC-inferior vena cava

aortic valve velocity can be obtained in the TG either at 0° deep TG or at 120° TG (Fig. 2.4). Finally, the aortic views are obtained by rotating the probe 180° degrees either clockwise or counterclockwise so that the probe is facing posteriorly to image the descending aorta and distal aortic arch (Fig. 2.5). An example in which TEE is extremely useful is in evaluation of mitral valve prolapse as shown in (Fig. 2.6).

Complications

Rates of major TEE complications range from 0.2 to 0.5 % and the rate of TEE associated mortality is estimated to be less than 0.01 %. The risk with the use of local anesthetics to anesthesize the oropharynx using benzocaines include

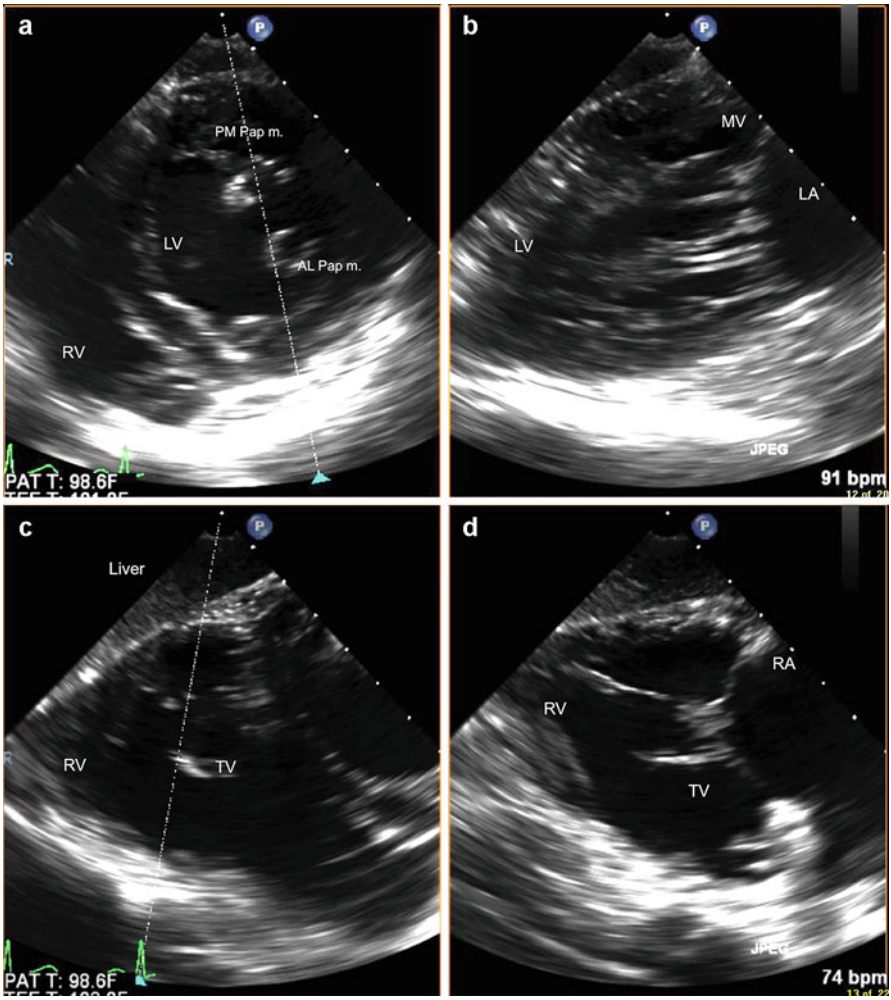

Fig. 2.3 TG (Transgastric) TEE images: (**a**) Short axis view (0°) of the LV showing the Al-anterolateral and PM-posteromedial papillary muscles. (**b**) X-plane through the short axis or multiplane at 90° shows the LV in long axis with mitral valve posterior and anterior leaflets. (**c**, **d**) Right sided views from the TG level are obtained by clockwise rotation of the probe. Panel (**c**) shows the TV-tricuspid valve in short axis and (**d**) in long axis

methemoglobinemia that presents as central cyanosis, oxygen desaturation, and brownish color to a blood sample. The risks associated with esophageal intubation include trauma to the oropharynx such as dental trauma, laryngeal/pharyngeal lacerations, bleeding, sore throat and hoarseness, laryngospasm/bronchospasm, and inadvertent tracheal intubation. Similarly, esophageal or gastric trauma, laceration,

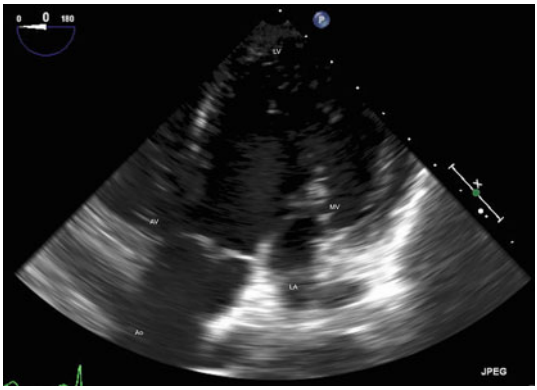

Fig. 2.4 TG TEE view of the aortic valve at 0° deep TG. Alternatively, the aortic valve velocity can be evaluated at 120° TG. These are the two views that are used in cases of aortic valve stenosis that produces the most parallel angle to the transducer for continuous wave flow interrogation

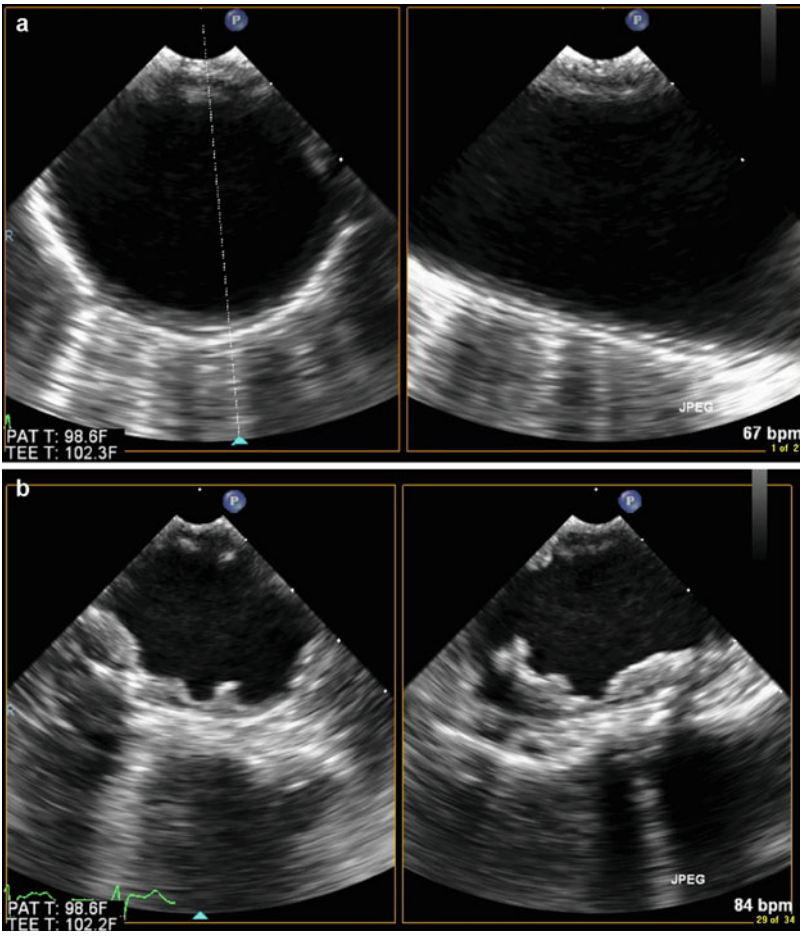

Fig. 2.5 Aortic TEE images: (**a**) Descending aorta in short axis (0°) and long axis (90°) showing absence of atherosclerosis. In comparison, panel (**b**) shows a severely diseased descending aorta with ulcerated atherosclerotic plaques

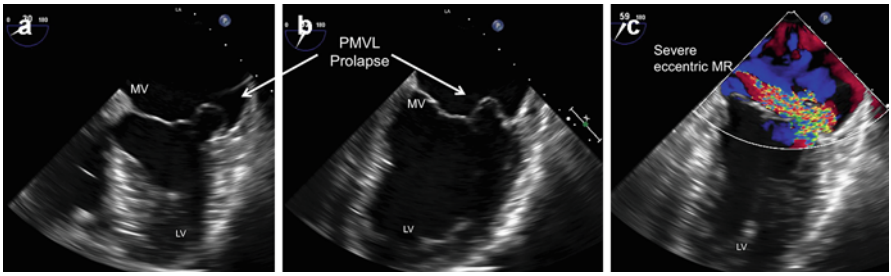

Fig. 2.6 Mitral valve prolapse images: (**a**, **b**) show severe prolapse of the posterior mitral valve leaflet (shown in *arrow*). Panel (**c**) shows severe eccentric mitral regurgitation with an anteriorly directed jet

bleeding, perforation and rupture can occur. The risk associated with sedation whether conscious sedation, MAC (Monitored anesthesia care), or general sedation include hypotension, respiratory depression, aspiration, arrhythmias, and even death. The risks of complications can be reduced dramatically by appropriate patient selection, careful manipulation of the probe during insertion and study, and experience in conscious sedation and the assistance of anesthesiology. Reversal agents should be available bedside in cases such as methemoglobinemia or respiratory depression. The reversal agents are methylene blue (1–2 mg/kg IV ×1) for methemoglobinemia, flumazenil (0.2 mg IV qmin) for benzodiazepines and naloxone (0.4–2 mg IV q2–3 min) for opioid overdose/reversal.

Clinical Vignettes

Case 1

Sixty-four-year-old female with a history of ovarian cancer, hyperlipidemia has been experiencing occasional palpitations over the last 3 months associated with occasional lightheadedness. Two weeks ago, the palpitations became more frequent and were associated with a few pre-syncopal episodes. In the ER, she was noted to be in atrial fibrillation with rapid ventricular response. TEE images are shown in (Fig. 2.7).

The TEE images show UE-upper esophageal views of the LAA-left atrial appendage that clearly shows a small thrombus (arrow). Therefore, cardioversion and catheter ablation are contraindicated. Thrombolytics have no role in treatment of LAA thrombi. The patient should receive at least 4 weeks of anticoagulation, followed up by re-evaluation and possible cardioversion.

Case 2

Fourty-two-year-old male with a history of polysubstance abuse and intravenous drug use (IVDU) presented to the ER with fever, shills, shortness of breath, with unstable vitals: hypotension (BP 70/35) and tachycardic (HR 135). A 2D echo was performed, followed by a TEE (Fig. 2.8).

The patient is presenting with hemodynamically unstable septic shock due to mitral valve endocarditis with a large vegetation (arrow) on the posterior mitral leaflet causing severe eccentric mitral regurgitation. The source is most likely due to IV drug use. The patient should be treated for antibiotics, however, considering the size of the vegetation, the severity of associated mitral regurgitation, he should be evaluated by cardiothoracic surgery.

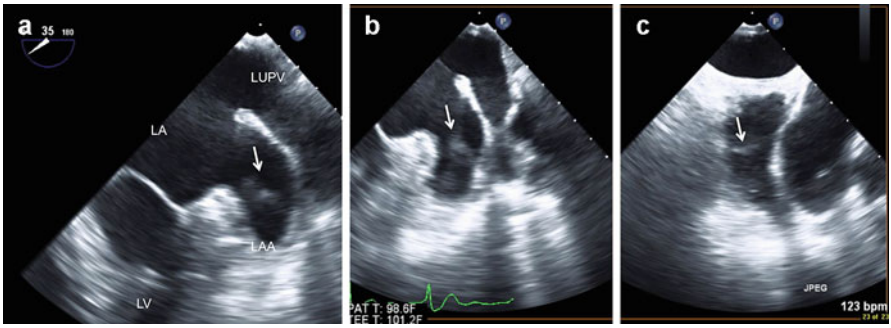

Fig. 2.7 (**a**–**c**) TEE views of the left atrial appendage in multi-plane angulations showing the presence of a thrombus

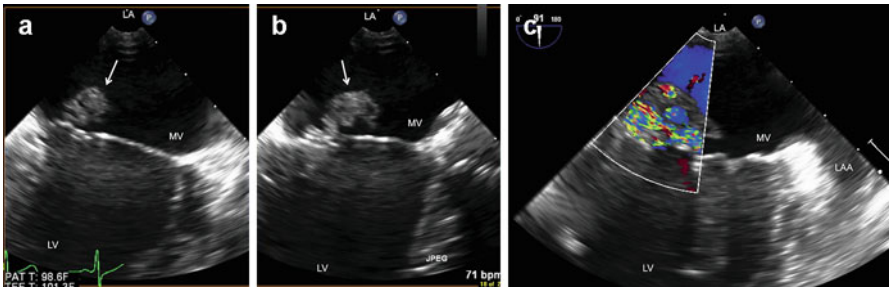

Fig. 2.8 (**a**), (**b**) Two chamber views showing the presence of a large vegetation on the mitral valve (**c**). Using color Doppler, severe eccentric mitral regurgitation can be visualized as a consequence of the vegetation

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Chapter 3
Contrast Echocardiography

Cesia Gallegos, Eddy Karnabi, and Robert C. Hendel

Despite the development of improved imaging techniques, contrast echocardiography (CE) may be indispensable in cases where optimal ventricular delineation is essential, as it enhances endocardial border delineation and offers assessment about intracardiac blood flow [1, 2].

The mechanism of the use of contrast with echocardiography lies in the principle of acoustic impedance, where the change in density from one medium to another causes reflection of sound waves, reason for the use of microbubble contrast agents since gas is less dense than blood.

Indications

Agitated saline provides contrast in the right heart and enables detection of shunts, the first clinical use of CE, as the microbubbles remain in the right heart and then diffuse into the lungs, unable to access the left heart unless a right-to-left heart shunt exists.

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The indications for CE with agitated saline use include:

1. Cardiac and extracardiac shunts: atrial septal defects (ASD) and ventriculoseptal defects (VSD)
2. Patient foramen ovale (PFO)
3. Structure identification, particularly the right heart
4. Evaluation of Tricuspid Regurgitation
5. Evaluation of Congenital heart disease

The assessment of left ventricular (LV) function is the most common indication for contrast use particularly for left ventricular opacification (LVO) in patients with suboptimal images, which happen in about 5–10 % of cases. The endpoint is to enhance the endocardial border definition (EBD), as well as assessment of dimensions, volume, and wall motion.

Indications for the use of contrast agents include [1–3]:

1. Assessment of LV function, especially when two or more segments are not seen on non-contrast images mainly due to respiration, and increased heart rate,
2. To delineate LV structure and measure volumes and ejection fraction
3. For definite diagnosis when the following are suspected: apical hypertrophic cardiomyopathy, ventricular non-compaction, apical thrombus, and complications of myocardial infarction such as LV aneurysm, pseudoaneurysm, and myocardial rupture.
4. For use with stress echocardiography when two or more segments of the LV are not well identified during stress, for the assessment of wall motion abnormalities, to increase accuracy, and increase the reader's confidence.
5. To assist in the detection and identification of intracardiac masses including tumors and thrombi.
6. To enhance Doppler signals when spectral profiles cannot be obtained with standard examination and are not visible.
7. Although not yet FDA approved, contrast injection can be used in myocardial perfusion imaging.

Contraindications

Although generally safe and effective, contrast agents have some contraindications:

- Hypersensitivity to an agent
- For perflutren protein-type a microspheres (Optison) or perflutren lipid microspheres (Definity)_ known hypersensitivity to blood, blood products, or albumin
- Fixed right to left, bidirectional or transient right to left cardiac shunts.

Equipment

For the detection of shunts, agitated saline is the method of choice. The saline contrast should be composed of bacteriostatic normal saline cannula agitated with 0.5 ml of room air, between two 10 ml syringes. For this, a three-way stopcock should be used, as well as a >20 gauge IV line, preferably in the right arm. The aim is to inject 5 ml of saline and 0.2 ml of air from one syringe to the other prior to immediate injection [1, 4].

There are three FDA approved contrast agents: Optison (GE Healthcare, Princeton, NJ), Lumason (Bracco Diagnostics Inc., Monroe Township, NJ; also known as SonoVue), Definity (Lantheus Medical Imaging, North Billerica, MA). Optison is perfluropropane gas on human albumin coating, whereas Definity uses the same gas but has a phospholipid shell. Other agents have been approved in Canada, Europe, some Latin American and Asian countries. These contrast agents are stable and small in size (2–6 um) allowing the passage through the pulmonary capillary bed and causing the opacification of the left sided chambers. Because small lumen catheters increase bubble destruction, for administration of contrast, a 20-gauge or greater needle is usually recommended. A flush is required for the use of contrast, hence is generally better to use a three-way stopcock.

Technique

Harmonic imaging the current standard technique for echocardiography, and its original use was to enhance the detection of contrast. Contrast microbubbles interact with the ultrasound waves in a nonlinear fashion and generates a second harmonic frequency that enhances the detection of the microbubbles. For its optimal use, the transmit power must be reduced from >1.0 to approximately 0.4–0.6. However this gives the possibility of contrast destruction with subsequent equivocal results in assessment of the myocardium [4]. Hence, there are contrast-specific imaging modalities, namely low-power, or low Mechanical Index (MI), which delivers best left ventricular opacification and endocardial border definition. MI in these cases is usually between 0.15 and 0.3. With the use of these techniques, less contrast is necessary, minimizing the risk for any adverse effects.

As mentioned above, an infusion pump can be used, as well as an IV bolus, or a diluted bolus, which must be set up prior to starting the procedure. During a rest study, the rate of IV bolus is usually 0.5–1.0 mL/s, with subsequent slow saline flush administration that is to be stopped when contrast is seen in the right ventricle. Repeat doses as necessary may be required. During stress, the contrast should be injected about 30 s prior to exercise termination. For the infusion method, the contrast should be diluted in a 10 ml syringe, or in a 50 ml bag of normal saline, after which the infusion rate must be adjusted. If using the 10 ml syringe, it is usually recommended to slowly push 0.5–1 ml every few minutes, whereas if the saline bag is utilized the rate will determined by the appearance of a contrast image, usually at 150–200 ml/h.

Data Interpretation

For conventional CE with agitated saline, the presence of contrast/bubbles in the left heart indicates the possibility of an intracardiac shunt. The bubbles created do not appear in the left chambers (as the size precludes its passage through the pulmonary capillaries) unless there is a communication between the right and left cardiac chambers in cases of right to left shunts. However, in case of a left to right shunt, negative contrast effect is visualized. For instance, a PFO is diagnosed when more than three bubbles pass from right to left within 34 cardiac cycles (Fig. 3.1). Based on the number of bubbles, the PFO is then defined as being small (3–10), medium (10–20), or large (>20 bubbles). If the bubbles are seen >5 cardiac cycles, a pulmonary arteriovenous malformation is suggested. With transthoracic echocardiography, the apical four-chamber view is used. Injection of agitated saline from the left arm, in comparison to the usual injection from the right arm, may help detect the presence of a persistent left superior vena cava (Fig. 3.2) draining into the coronary sinus. Agitated saline bubbles strengthen the Doppler signals from the right heart chamber and augments the tricuspid regurgitation (TR) signal to record the TR gradient used to calculate the right ventricular systolic pressure (RVSP).

In particular cases, for example, in the evaluation of LV masses or thrombi, contrast agents have been shown to improve its diagnosis. A thrombus for instance, is usually seen as a non-opacified structure. Contrast is also useful for the diagnosis of non-compaction, in which the addition of an agent allows for the myocardial layers to be clearly displayed and the ratio to be calculated (2:1 non compacted to compacted myocardium is the usual finding). Contrast can be used in the identification

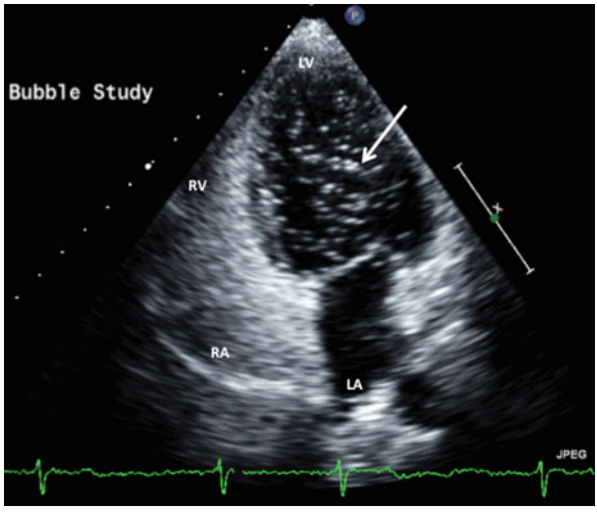

Fig. 3.1 Bubble study with Saline injection showing the presence of a PFO with saline bubbles opacifying the right-sided chambers and multiple bubbles passing into the left cardiac chambers (*arrow*)

of complications of myocardial infarction such as LV aneurysm, pseudoaneurysm, and myocardial rupture.

CE for stress testing also yields important information, given that images tend to be worse during stress. Thus, addition of contrast provides a marked improvement in images, and increases the percentage of wall motion abnormalities visualized.

Complications

As mentioned earlier, CE is generally safe, however side effects have been noted, but tend to be mild and transient, although severe hypersensitivity reactions have been reported. In clinical trials, the most common side effects per contrast agents were [4]:

- SonoVue: Headache (2.1 %), Nausea and chest pain (1.3 %)
- Optison: Headache (5.4 %), Nausea and/or vomiting (4.3 %) warm sensation or flushing (3.6 %), dizziness (2.5 %)
- Definity (Luminity): Headache (2.0 %), flushing (1.0 %) Back pain (0.9 %) rash, urticarial, anaphylaxis.

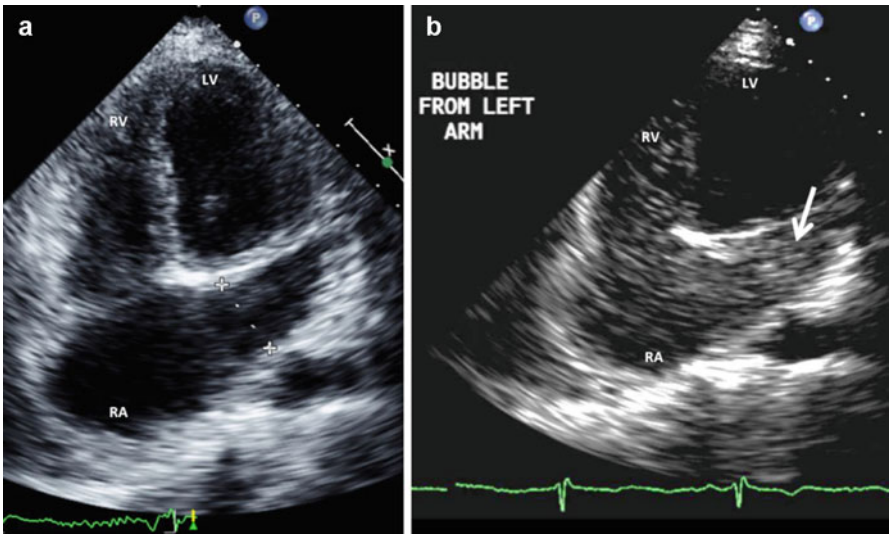

Fig. 3.2 Use of contrast in delineating unknown structures (**a**) Four chamber view showing the presence of a persistent left SVC (PLSVC). (**b**) A bubble study with the use of saline injection from a left arm vein confirms the presence of the persistent left SVC (*arrow*) draining into the coronary sinus (enlarged). PLSVC is a common variation of the thoracic venous system. In isolation, this entity is benign but it is frequently associated with other cardiac abnormalities

In summary, contrast agents are safe, effective, and recommended for use with echocardiography, improving the results of echocardiographic imaging studies [4, 5].

Clinical Vignettes

Case 1

78 year-old male with history or prior anterior wall myocardial infarction, hypertension, hyperlipidemia presented to the hospital with left sided weakness for 3 days duration. In ER, as part of his evaluation, a 2D echocardiogram was performed. For better assessment of LV apex, contrast was injected. Images are shown in (Fig. 3.3).

This case shows the presence of apical infarction with akinetic segment and the presence of a moderate size apical aneurysm with a thrombus on a stalk (arrow), that is clearly detected with contrast but can sometimes be missed during a standard echocardiographic examination. In such cases, anticoagulation is recommended.

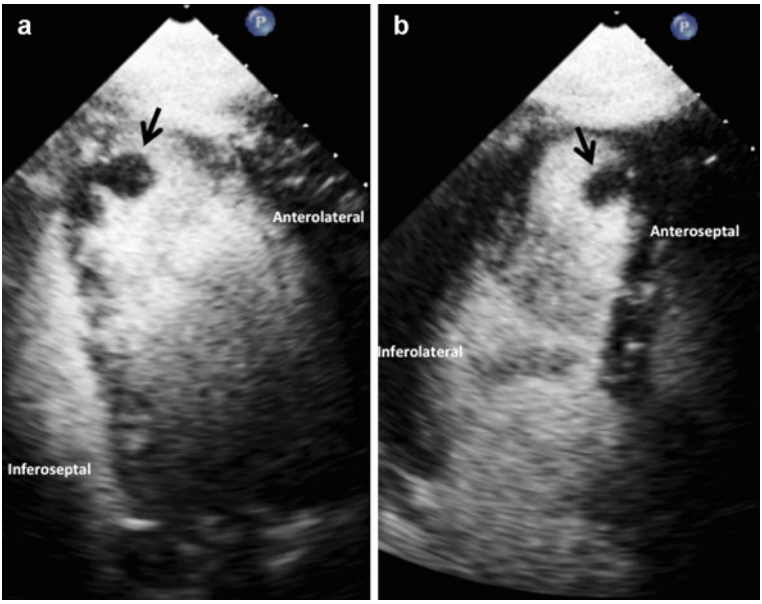

Fig. 3.3 Use of contrast in delineating area of infarction and thrombus. Panel (**a**) and (**b**) demonstrates apical aneurysm with a thrombus on a stalk (*arrow*). See Case #1 text for details

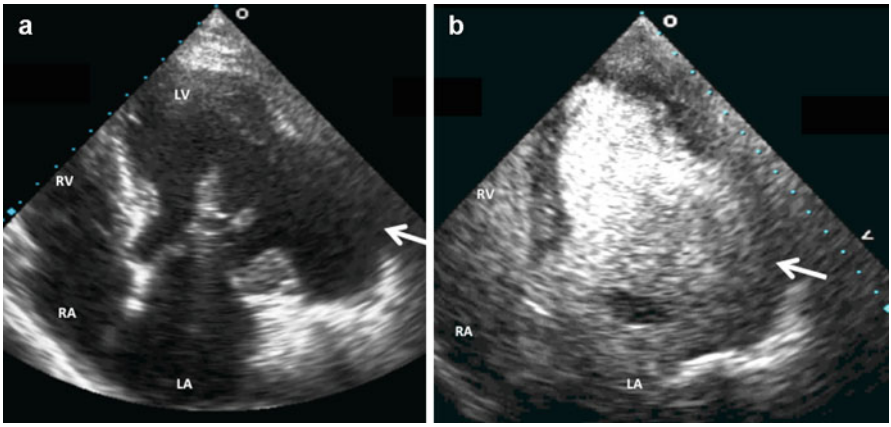

Fig. 3.4 Use of contrast in echocardiography to identify and delineate post-MI aneurysm (*arrow*). (**a**) Four-chamber view without contrast. (**b**) Anterolateral aneurysm noted with contrast. See Case #2 text for details

Case 2

85 year-old female with no significant cardiac history presented to the hospital with 2 weeks of chest pain and shortness of breath. While in the ER, she was noted to be in cardiogenic shock requiring inotropic and pressor support. A STAT echo performed is shown in (Fig. 3.4).

The images shown represent a complication of myocardial infarction with A. without contrast and B. with contrast. The use of contrast clearly helps in establishing the diagnosis of an anterolateral aneurysm as a complication of MI.

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Chapter 4
Exercise Stress Testing

Eddy Karnabi

Exercise testing (ET) is a well-validated procedure for the diagnosis of coronary artery disease (CAD) and assessing functional capacity and prognosis. Exercise stress tests may detect myocardial ischemia along the ischemic cascade (Fig. 4.1) as a result of a mismatch between myocardial oxygen delivery (from coronary blood flow impairment) and myocardial oxygen demand. It is simple and easy to perform the test, with minimal equipment required.

There is two types of exercise stress tests that can be performed: bicycle and treadmill with the latter being the most widely used in the US. The advantages that bicycle ergometry have over treadmill is the ability to be performed in patients with weight bearing problems, patients with gait/balance and orthopedic abnormalities, a cleaner (less noise) ECG for interpretation, and the ability to take direct measurements of workload in watts which has a linear relationship with myocardial oxygen consumption (MVO2).

Indications

The most common indications according to the 2002 ACC/AHA guidelines for exercise testing and the 2014 guidelines for stable ischemic heart disease [1–3] are (Table 4.1).

Most commonly, ET is used in the diagnosis of ischemic heart disease in patients with intermediate pretest probability of CAD and/or risk stratification of patients with intermediate or high pretest probability of CAD based on age, gender, and symptoms (Table 4.2).

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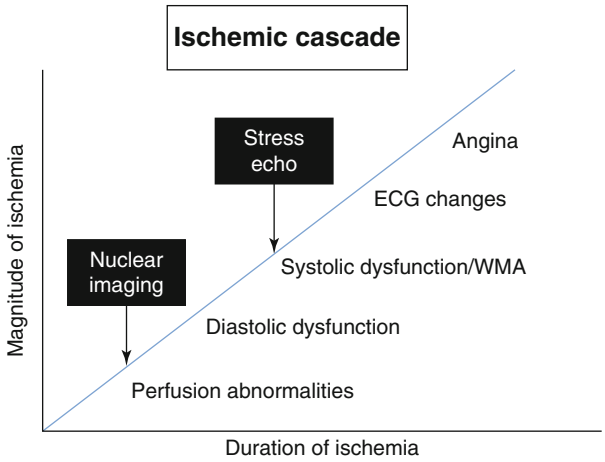

Fig. 4.1 The ischemic cascade: represent the magnitude of ischemia in relation to the increasing duration of ischemia. The initial changes seen are perfusion abnormalities detected with nuclear myocardial perfusion imaging. With increasing ischemia, diastolic dysfunction followed by systolic dysfunction occurs. At this stage, wall motion abnormalities (WMA) are detected by stress echocardiography. It is only at the late stages, that ECG changes and angina develops

Table 4.1 Indications for exercise ECG stress testing

1.	Symptoms suggestive of CAD
2.	Acute chest pain after ACS is ruled out
3.	Recent ACS not treated with coronary angioplasty
4.	Known CAD and change in clinical status
5.	Prior incomplete revascularization
6.	Valvular heart disease
7.	Newly diagnosed cardiomyopathy
8.	Certain cardiac arrhythmias
9.	Pre-op cardiac assessment prior to non-cardiac surgery

Table 4.2 Pretest probability of CAD

Age (year)	Gender	Typical/definite angina	Atypical/probable angina	Non-anginal chest pain	Asymptomatic
30–39	Men	Intermediate	Intermediate	Low	Very low
	Women	Intermediate	Very low	Very low	Very low
40–49	Men	High	Intermediate	Intermediate	Low
	Women	Intermediate	Low	Very low	Very low
50–59	Men	High	Intermediate	Intermediate	Low
	Women	Intermediate	Intermediate	Low	Very low
60–69	Men	High	Intermediate	Intermediate	Low
	Women	High	Intermediate	Intermediate	Low

There are several conditions in which exercise tests should be combined with an imaging modality; either myocardial perfusion imaging (MPI-SPECT or PET) or echocardiography. These conditions include: ventricular paced rhythm, left bundle branch block (LBBB), pre-excitation (Wolff-Parkinson-White syndrome), >1 mm ST depression at rest, patients taking digoxin, previous PCI/CABG, left ventricular hypertrophy (LVH), and right bundle branch block (RBBB) which precludes ST segment interpretation in leads V1–3.

ET may also be used for patients with valvular heart disease (such as mitral stenosis, aortic stenosis, and aortic regurgitation) to assess for symptoms; this is usually performed in conjunction with echocardiography.

Contraindications (Table 4.3)

Table 4.3 Contraindications to exercise stress testing [1]

Absolute contraindications to exercise stress testing
Acute myocardial infarction (within 2 days)
High risk unstable angina
Uncontrolled cardiac arrhythmias
Symptomatic severe aortic stenosis
Uncontrolled symptomatic heart failure
Acute pulmonary embolus or pulmonary infarction
Acute myocarditis or pericarditis
Acute aortic dissection
Relative contraindications to exercise stress testing
Left main coronary stenosis or it's equivalent
Moderate stenotic valvular heart disease
Electrolyte abnormalities
Severe arterial hypertension
Tachyarrhythmias or bradyarrhythmias
Hypertrophic cardiomyopathy and other forms of outflow tract obstruction
Mental or physical impairment leading to inability to exercise adequately
High degree atrioventricular block

Equipment

The equipment for a treadmill ECG stress test includes the treadmill, ECG electrodes, BP cuff, and the recording computer system that controls the stress testing protocol being used. In addition, a physician or physician assistant/nurse practitioner should supervise the test (with a physician on site). The exercise protocols in practice are the Bruce protocol, Modified Bruce protocol, Naughton,

Table 4.4 Bruce protocol

Stage	Minutes	% Grade	MPH	METS
1.	3	10	1.7	5
2.	6	12	2.5	7
3.	9	14	3.4	10
4.	12	16	4.2	13
5.	15	18	5.0	15
6.	18	20	5.5	18
7.	21	22	6.0	20

Blake, and Cornell protocols. Each varies according to the speed and grade parameters. The Bruce protocol is the most widely used and validated; the protocol is divided into 3-min stages that increase in speed and inclination (Table 4.4).

The disadvantages of the Bruce protocol is the large variations in workload between stages and therefore, lowering the diagnostic sensitivity and reducing the value in evaluating functional capacity. The modified Bruce protocol provides a lower workload for patients with poor cardiovascular fitness and in less fit/sedentary and older individuals with stages of 0 and ½ being included at 0 and 5% grades respectively at 1.7 MPH. The Naughton protocol is well suited for older debilitated patients (less intense); with the Blake protocol for younger and fit patients; In addition, the ramp protocol is especially useful in heart failure patients in conjunction with cardiopulmonary metabolic testing.

Technique

The tests starts with patient preparation: NPO for at least 4–6 h and instructed to bring comfortable clothing and shoes for the procedure. A thorough review of the patients' history, medications and physical exam should be performed. A proper indication as listed in Table 4.1 should be reviewed. The patient should sign an informed consent after explaining the indication, possible complications and risks of the procedure, which include a risk of 1:10,000 of a serious adverse event (MI or death), and alternative testing. If the test is being done for the diagnosis of CAD, then certain cardiovascular drugs should be withheld if possible, such as beta-blockers, non-dihydropyridine calcium channel blockers (diltiazem and verapamil), and digoxin, certain antiarrhythmics (e.g. Amiodarone and sotalol), or anti-anginal medications (nitrates); this ideally should be done after discussion and under the supervision of their supervising physician. If the test is for functional purpose or to assess symptoms or ischemia, on optimal medical treatment, then cardiovascular medications should be continued.

The next step is to choose the optimal stress test to achieve a satisfactory workload. The choice is usually between a Bruce and Modified Bruce protocol depending on the patients' ability to exercise appropriately to reach the target heart rate response, which is 85 % of his/her age, predicted maximal heart rate (APMHR) (220-Age.) A patient's capacity is also predicted based on the reported activity level and direct observation prior to the test. The preferred approach is a symptom-limited exercise testing and not simply achieving 85 % of the APMHR.

A baseline ECG should be performed to exclude significant abnormalities that can render the ECG non-diagnostic such as: pre-excitation (Wolff-Parkinson-White syndrome), ventricular-paced rhythm, left bundle branch block (LBBB), more than 1 mm ST depressions at rest, digoxin use with associated ST abnormalities, and left ventricular hypertrophy (LVH) with ST-T wave abnormalities. Next the patient is instructed on the body position during the treadmill exercise by walking erect, near the front of belt with the hands resting on the handrail.

Data are obtained during each stage of the protocol and in recovery with attention paid to any ST depressions or elevations and arrhythmias. Blood pressure measurements should be performed prior to exercise and during the last minute of each stage, as well as during recovery. A normal hemodynamic response to exercise is an increase in systolic and decrease in diastolic pressures. The patient should be visually monitored for any signs of distress and asked frequently about the development of symptoms such as exercise limiting or non-limiting angina. As mentioned, most exercise stress tests should be symptom limited maximal stress tests. Achievement of 85 % of APMHR is not an indication for termination of the test. The testing endpoints can be patient related or physician related. In general, if a patient is requesting to stop, it is usually an indication to terminate the test especially if it is associated with symptoms (such as chest pain, dyspnea, dizziness, claudications and fatigue) or arrhythmia. The clinician on the other hand, can decide to terminate the test if there are marked ST depressions or elevations, a new bundle branch block that cannot be distinguished from ventricular tachycardia (VT), new high grade AV block, sustained VT or ventricular fibrillation, increasing frequency of ventricular ectopy, and onset of supraventricular tachyarrhythmias, as well as hypotensive BP response to exercise.

Table 4.5 lists the absolute and relative indications for terminating exercise testing:

If the test is performed in conjunction with myocardial perfusion imaging, the radiopharmaceutical is injected as close to the peak exercise and the patient encouraged to exercise for at least 1 min after the injection.

Post-exercise recovery period should follow the termination of the test; the patient should be continued to be monitored until the HR < 100–110 and SBP < 160 or at the baseline level. It is common and not pathologic for the BP to fall in the immediate post-exercise period.

Table 4.5 Indications for terminating exercise testing

Absolute indications
Drop in systolic blood pressure of >10 mmHg from baseline BP despite an increase in workload, when accompanied by other evidence of ischemia
Moderate to severe angina
Increasing nervous system symptoms (e.g., ataxia, dizziness, or near-syncope)
Signs of poor perfusion (cyanosis or pallor)
Technical difficulties in monitoring ECG or systolic BP
Subject's desire to stop
Sustained ventricular tachycardia
ST elevation (≥1.0 mm) in leads without diagnostic Q-waves (other than V1 or aVR)
Relative indications
Drop in systolic BP of ≥10 mmHg from baseline BP despite an increase in workload, in the absence of other evidence of ischemia
ST or QRS changes such as excessive ST depression (>2 mm of horizontal or downsloping ST-segment depression) or marked axis shift
Arrhythmias other than sustained ventricular tachycardia, including multifocal PVCs, triplets of PVCs, supraventricular tachycardia, heart block, or bradyarrhythmias
Fatigue, shortness of breath, wheezing, leg cramps, or claudication
Development of bundle-branch block or IVCD that cannot be distinguished from ventricular tachycardia
Increasing chest pain
Hypertensive response (systolic BP of >250 mmHg and/or a diastolic BP > 115 mmHg)

Data Interpretation

Interpretation should be performed by an experienced physician. The test can be positive, negative, or non-diagnostic. A test is non-diagnostic if the patient does not achieve the target heart rate of 85 % (APMHR = 220-age), or if the baseline ECG is abnormal making the ST changes un-interpretable during exercise. In such cases, the ET is combined with an imaging modality.

The data are analyzed for ECG abnormalities, arrhythmias, symptoms, and functional capacity.

ECG abnormalities ST-segment changes deviating from the isoelectric line (determined by the PR segment) are measured 80 milliseconds (ms) beyond the J-point. A normal response to exercise is <1 mm ST horizontal or downsloping depressions, or <15 mm when upsloping ST depression is noted (Fig. 4.2). A few diagnostic principles for interpreting ET are: (1) The more leads with ST changes present, the higher probability of ischemia; (2) ST depressions do not localize ischemia to an area of the myocardium; (3) horizontal or downsloping ST depression >1 mm and upsloping depression of >2 mm is abnormal; (4) ischemic ST depression usually occur in the lateral leads (I, V4–6); (5) isolated inferior changes are usually false positive findings secondary to diaphragmatic motion and/or atrial repolarization; (6) changes in R wave amplitude or T wave inversion

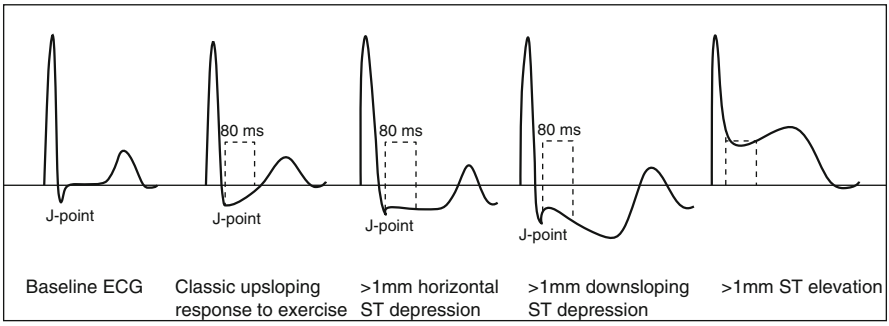

Fig. 4.2 ST segment changes at baseline and during exercise. Classic normal upsloping is seen in normal individuals if the ST segment returns to the isoelectric line by 80 ms after the J-point. Abnormal responses are >1 mm horizontal, downsloping and upsloping ST depressions 80 ms past the J-point

are not specific markers of ischemia; (7) ST elevation in the setting of Q-waves, represent a prior MI and is the result of abnormal wall motion such as in dyskinetic segment or aneurysm; (8) ST segment elevation represents ischemia and may localize the area of ischemic myocardium; (9) U wave inversion may be associated with ischemia.

Arrhythmias Sustained VT and VF although rare, are abnormal findings that should prompt further evaluation.

Time to recovery of both ST changes and heart rate are two additional parameters to analyze. If rapid recovery (<1 min) of ST changes occurs, the less likelihood ischemia is present. Heart rate recovery is another important prognostic indicator. It is considered abnormal if the difference between maximum HR at peak stress and at 1 min into recovery is 12 beats or less.

Blood pressure monitoring is another important aspect of exercise testing for safety and diagnostic reasons. A normal hemodynamic response is an increase in systolic BP and a decrease in diastolic BP. The test can be terminated if there is a drop of systolic BP with increasing workload especially to below the resting BP or excessive systolic BP elevation (SBP > 260). The patient's symptoms should be recorded throughout the procedure and reported.

Prognosis The Duke Treadmill Score (DTS) calculated as: exercise minutes – (5 × maximal ST changes) – (4 × angina score) is an important predicator of mortality. The angina score is defined as no angina = 0, non-limiting angina = 1, and limiting angina = 2. A low DTS score is >5, intermediate risk DTS −10 to <5, and high risk DTS < −10. The functional capacity is calculated based on the exercise time with an exercise period of 6 min yielding 7 METS; this is associated with a lower mortality rate independent of any ST changes.

Diagnostic accuracy The sensitivity of exercise stress tests is approximately 68 % and specificity of 70 %, which can be improved with careful patient selection. Myocardial perfusion imaging with exercise stress testing enhances the diagnostic sensitivity and specificity especially in patients with patients with resting ECG abnormalities as mentioned above.

Complications

Complications of exercise testing are rare especially in the healthy low risk patients and increases in the CAD and arrhythmia patients. Arrhythmic events are common in those with a history of prior arrhythmia and can occur in up to 10 %; on the contrary, in healthy subjects the overall incidence is approximately 0.1 %. The most common arrhythmia is atrial fibrillation. VT and VF are rare and occur in 6 per 10,000 tests and <1 per 10,000 test respectively. Death is extremely rare but may occur in 1 per 25,000 tests. Other cardiovascular complications include ischemia with angina and infarction, brady-arrhythmias such as bundle branch blocks and AV blocks, congestive heart failure, hypertension, hypotension and aneurysm rupture. Non-cardiovascular complications include pulmonary (asthma, bronchospasm, exacerbation of underlying pulmonary disease), gastrointestinal (nausea, vomiting), neurological (dizziness, syncope, stroke), and musculoskeletal (muscle cramps, joint pain, exacerbation of musculoskeletal disease, back pain) which are more common.

Clinical Vignettes

Case 1

Fifty year old male with hypertension and hyperlipidemia who has been experiencing episodic chest discomfort during lifting and with heavy exertion. The pain is described as a sharp pain in the mid chest without any radiation. His baseline ECG was normal. His primary care physician sent him for an exercise ECG stress testing. He was able to exercise for 5:29 min at which point the test was terminated after he started experiencing non-limiting chest pain and the ECG findings as noted in (Fig. 4.3). *His blood pressure at peak stress was 152/68.*

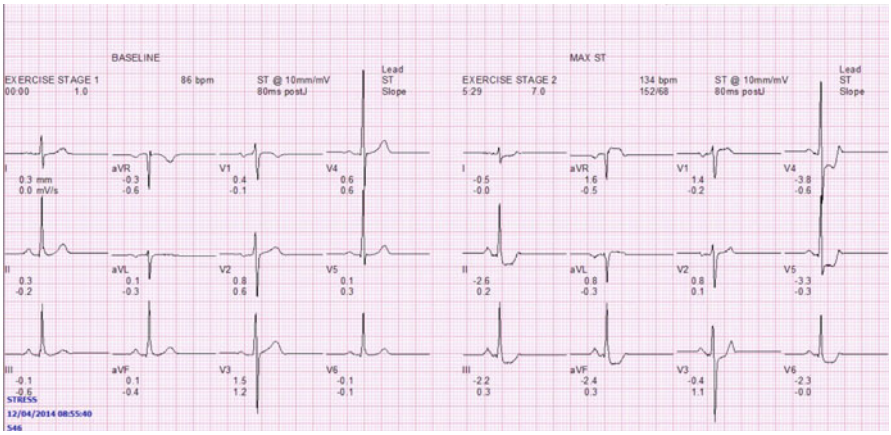

Fig. 4.3 Case #1 (see text for details)

The case presents a patient in the intermediate risk group with atypical chest pain. According to Bayes theorem and the appropriateness criteria, he should undergo an exercise stress test especially with a normal baseline ECG. During maximal exercise, the patient experienced chest pain with >2 mm ST depressions in inferior leads and >3 mm ST depressions in lateral leads (V4–6). This is considered a positive response. The patient had a cardiac catheterization that showed 95 % stenotic left circumflex artery.

Case 2

Sixty-eight-year-old female with history of left breast cancer s/p mastectomy and radiation, *hypertension*, *tobacco use is being evaluated for pre-op testing and risk stratification prior to contralateral mastectomy. A stress test was ordered. She was able to reach stage 3 when suddenly she started feeling palpitations and lightheadedness. The tracings are shown in* (Fig. 4.4).

The tracings show the patient converting from sinus tachycardia to a sustained ventricular tachycardia, which is an abnormal response indicative of ischemia or infarction and is associated with a worse outcome and increased mortality. Further evaluation is warranted.

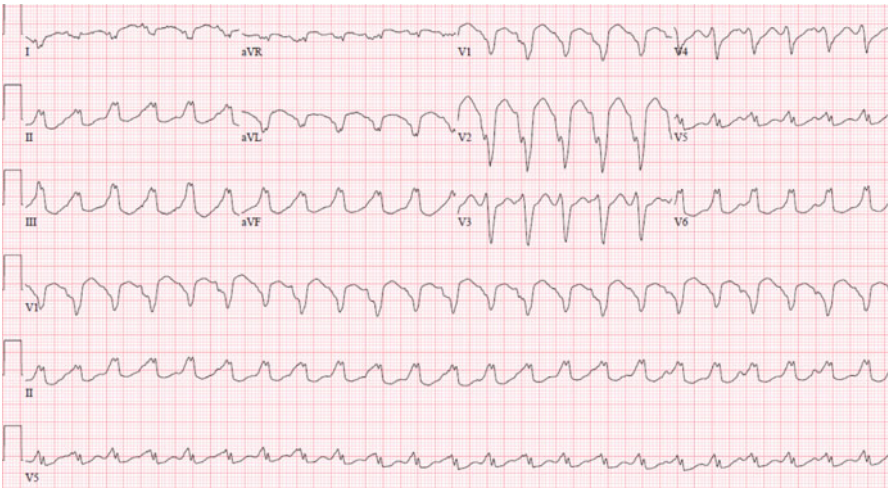

Fig. 4.4 Case #2 (see text for details)

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Chapter 5
Cardiopulmonary Exercise Testing

Alexis P. Rodriguez

Introduction

The concomitant gas exchange measurement furthers the modality of exercise testing by estimating oxygen consumption at different exercise intensities. Oxygen consumption, in turn, can be approximated to the measurable metabolic equivalent (MET). Cardiopulmonary exercise testing (CPET) remains the sole method for the direct MET measurement. During this test, many variables are recorded including the expiratory ventilation, pulmonary gas exchange (oxygen uptake and carbon dioxide output), along with electrocardiogram (ECG) and blood pressure recordings [1].

Indications

Assessment of a patient with CPET allows for the evaluation of unexplained dyspnea, exercise intolerance, and cardiopulmonary disease extent including the evaluation of patients with heart failure. Additionally, there are new emerging applications of this diagnostic tool including the evaluation of congenital heart disease in adults, pulmonary hypertension, arrhythmia-induced heart failure, rate-response and biventricular pacemaker evaluation, disability-fitness assessment, and even prior to pulmonary resection. As more clinicians familiarize with this test, and data continue to emerge, CPET applications will continue to broaden including in the distinction and evaluation of pulmonary versus cardiac pathologies [1].

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Contraindications

Absolute contraindications include acute myocardial infarction, unstable angina and arrhythmias, acute myopericarditis, severe symptomatic aortic insufficiency, acute pulmonary embolism, uncontrolled asthma, and cognitive impairment limiting subject's cooperation. The ordering clinician should also be aware of relative contraindications. These include, left main (or three-vessel) coronary disease, severe uncontrolled (pulmonary) hypertension, high degree AV block, hypertrophic cardiomyopathy, moderate valvular stenosis, pregnancy, and orthopedic impairment. Furthermore, the test should be terminated early at the patient's request, severe ischemia on ECG, extreme blood pressure responses, hypoxia, among others. On the other hand, some patients report discomfort with the facemask, mouthpiece, or nose clip. Thus, all these should be addressed before starting the test. While all these appear commonsense, they serve to prove the need for comprehensive initial patient assessment, and close monitoring during the exam.

Equipment

The CPET aim is to progressively increase subject's workload as tolerated. This can be attained by exercising the individual on either a treadmill or cycle ergometer. The former is generally considered more appropriate for active subjects while also allowing for higher oxygen consumption. On the other hand, the latter is preferred in those at risk of falls, requires less training, and allows for blood pressure recording more expeditiously. Besides the treadmill or cycle ergometer, the patient is outfitted with either a mask or mouthpiece for the gas sampling. Blood pressure is also reordered serially throughout the test. A metabolic cart is used to measure the expire gases. For accurate recordings, this system should be monitored and meticulously calibrated to produce consistent results [2]. Figure 5.1 shows the air sealed mask used for gas analysis.

Fig. 5.1 Air-sealed face mask with tubing connected to gas analyzer, used to determine gas flow and values during metabolic testing

Technique

Different testing protocols have been developed for functional testing. Patient capabilities and diagnostic goals generally determine the choice of CPET and protocol modality. However, the principle is similar for all these, and requires the incremental monitored exercise effort until maximal exertion is reached. Some of these include the Balke and Ware, Naughton, and ramp protocols. Irrespective of the one used, it should be individualized and tailored to yield fatigue-limited exercise, which, in ideal circumstances, should occur between 8 and 12 min. Shorter evaluations produce unreliable non-linear relationships between oxygen uptake and work performed. Contrariwise, more protracted regiments may result in testing termination due to specific muscle fatigue, as opposed to cardiopulmonary endpoints. Finally, patients should be discouraged from significant handrail support since it alters the relationship between oxygen uptake and work, by effectively reducing the latter for any given measurement of the former.

Data Interpretation

During exercise, oxygen uptake (Vo_2) can be estimated by the Fick Equation:

$$Vo_2 = (SV \times HR) \times (Cao_2 - Cvo_2)$$

SV represents the stroke volume, HR the heart rate, Cao_2 the arterial oxygen content, and Cvo_2 the mixed venous oxygen. At maximal exercise, this equation would reflect the subject's ability to take in, exchange, transport, and utilize oxygen for aerobic metabolism. The Vo_2response to exercise is linear until a maximum is reached, and then begins to plateau. With higher metabolic workloads, the arteriovenous oxygen difference increases, which is a physiologic response best noted in trained athletes. On the other hand, exercise intolerance is evidenced by any changes in the Fick equation that results in an abnormally low Vo_2max, such as suboptimal maximal heart rate response, decrease stroke volume, decrease in Cao_2, or increase in Cvo_2 [3].

Other important estimations include the respiratory exchange ratio (RER) and the ventilatory anaerobic threshold (VAT). The former is calculated by dividing the carbon dioxide output by the oxygen uptake. The RER is determined by the main source of metabolic fuel used; with a ratio of 1 indicative of carbohydrates while <1 represents a mix of carbohydrates and fat, or protein. RER may increase during exercise due to either buffered lactic acid or hyperventilation. Conversely, VAT, or anaerobic threshold, is a determinant of exercise capacity. This principle relies in the fact that at lower workloads metabolism is mostly aerobic whereas there is a shift to lactate production with increasing exercise intensity. The VAT can be deter-

mined by directly measuring blood lactic acid or bicarbonate content, or less reliably through non-invasive techniques. Figure 5.2 shows a metabolic test graph report. Normal parameters for CPET and patterns of abnormal results are shown in Tables 5.1 and 5.2, respectively.

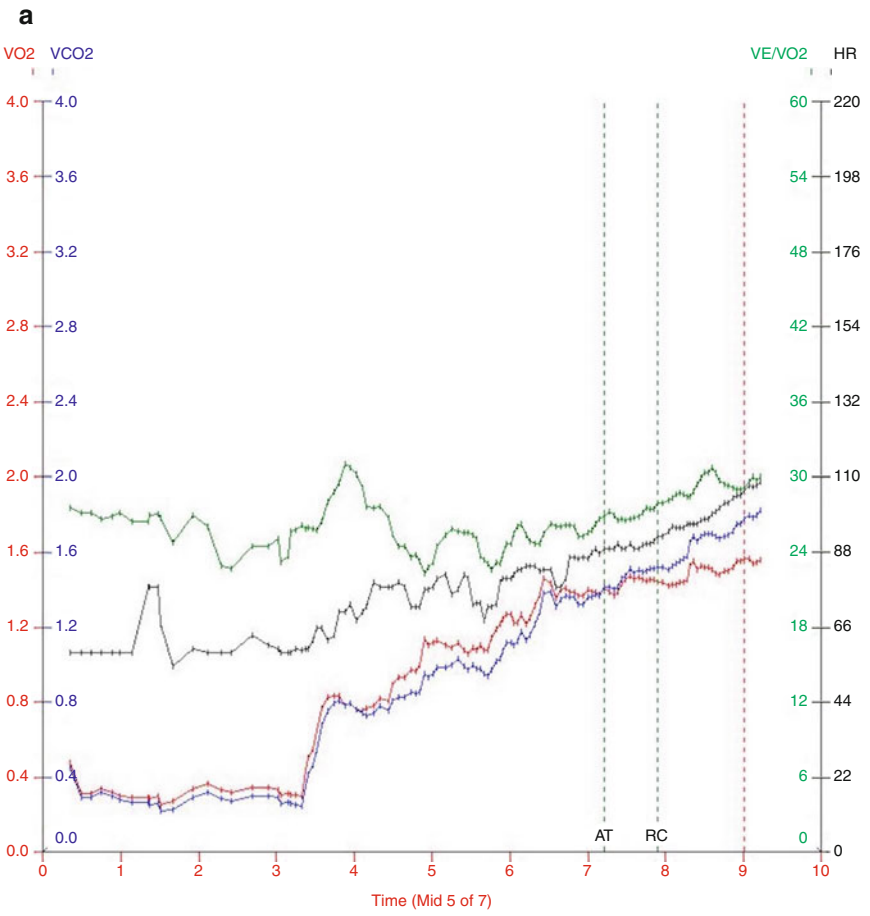

Fig. 5.2 Exercise metabolic test of a patient with history of heart failure. Panel **a** demonstrates the continuous calculation of metabolic information, with the horizontal axis corresponding to time in minutes. The *green curve* represents VE/V_{O2}, heart rate in *black*, V_{O2} in *red*, and V_{CO2} in *blue*. The *vertical line* labeled AT represents the aerobic threshold whereas RC represents the beginning of the recovery portion of the test. AT is reached at the point where the V_{O2} and V_{CO2} curves cross each other. From this point, V_{CO2} continues to be generated linearly whereas V_{O2} reaches a plateau. Panel **b** lists all of the quantitative data. In this patient, the exertion portion started at 3:15 min, AT was reached at 7:13 min, and maximal V_{O2} at 9:01 min. RER was 1.14, functional capacity was less than 75 % of predicted, V_{O2} at anaerobic threshold was 13.7 ml/kg/min in the range of 40–49 % of the predicted maximum. The heart rate reserve was high while on beta blocker, over 15 %. The VE/V_{O2} was 24.4

b

Spirometry						
	_	FVC	FEV1	1/FVC	MVV	_
Predicted		5.13	3.95	77	152	
Pre						
% Predicted						

Exercise						
	Rest	AT	VO2 Max	Pred	AT / VO2 Max (%)	VO2 Max/pred (%)
Time (min)	3:15	7:13	9:01			
Ex time (min)		3.56	5.44			
Speed (MPH)	1:1	2.7	2.6		104	
Grade (%)	0:0	14:0	20:9		67	
Borg PE						
---- Oxygen Cons						
VO2 (mL/kg/min)	3.0	13.7	15.2	28.7	90	53
VO2 (mL/min)	310	1407	1569	2955	90	53
VCO2 (mL/min)	256	1413	1481	3576	79	50
RER	0.83	1.00	1.14		88	
METS	0.9	3.9	4.4	8.2	90	53
---- Ventilation						
VE BTPS (L/min)	8.0	37.8	45.8	158.0	83	29
Vt BTPS (L)	0.68	2.04	2.43		84	
RR (br/min)	12	19	19		98	
BR (%)	94.9	76.1	71.0		107	
VE/VO2	26	27	29	37	92	78
VE/VCO2	31	27	26	31	104	83
VE/MVV (%)						
---- Cardiac ----						
HR (BPM)	60	89	106	167	84	64
VO2/HR (mL/beat)	5	16	15	18	107	84
sysBP (mmHg)	110	128	128		100	
diaBP (mmHg)	88	80	80		100	
SpO2 (%)						

Fig. 5.2 (continued)

CPET Complications

The most widely reported complications are those associated with exercise testing (Chap. 4). and include fatigue, shortness of breath, cardiac arrhythmia, syncope, and bronchospasm albeit unusually. The others are more complicated and may require intervention, which can range from medications to more advanced techniques such as cardioversion for unstable arrhythmias. Intolerance of the mask may be a complication preventing adequate data collection.

Table 5.1 Predicted normal parameters for CPET

Variable	Predicted and normal range values
VO_2, max (ml/min)	Based on age, gender, and height
	Lower limit of normal <80 % predicted
Resting VO_2, (ml/min)	150 + (6 × weight in kg)
	250–300 in larger obese individuals
Peak Heart Rate (bpm)	220 – age
	210 – (age × age)
	90 % predicted ± 15 bpm
Oxygen Pulse (mL/beat)	(Predicted VO_2, max)/(Predicted max HR)
	Normal – 80 % predicted (about 15 mL/beat in men, and 10 mL/beat in women)
Minute ventilation (L/min)	Peak Exercise: 70–80 % of MVV
Maximum tidal volume	60 % of functional vital capacity
V_E/VCO_2	Early in exercise 25–35
V_E/VO_2	Early in exercise 25–35
V_D/V_T	0.25–0.35 at rest
	Should decrease with exercise
$P_{ET}CO_2$ (mmHg)	38–42
	Declines after ventilator support
$P_{ET}O_2$ (mmHg)	95–100
	Rises after ventilator support
A-a O_2 gradient	Rest: 10–20
	Peak exercise: 15–30
S_aO_2 (%)	>95 % and should remain constant throughout
Respiratory exchange ratio	Rest: 0.6–1.0
	Peak exercise: 1.1–1.3

Clinical Vignettes

Case 1

A 54 year-old gentleman with a history of heart failure with reduced ejection fraction (HFrEF) of non-ischemic etiology is referred by his heart failure physician. His EF has been less than 30 % for the last 2 years. He is compliant with his goal-directed optimized medical regiment, and over the last year he received a bi-ventricular pacemaker, upgraded from his prior AICD. He has not been admitted for symptom exacerbation over the last 6 months, but complaints of shortness of breath with minimal exertion. He has otherwise, no significant medical comorbid conditions, and has a reliable social and family support. The patient undergoes CPET and his oxygen uptake (Vo_2) is calculated at 9 ml/kg/min, and his respiratory exchange ratio (RER) is estimated at 1.20.

Table 5.2 Cardiopulmonary exercise testing patterns in normal and individuals with various pathologies

Cardiopulmonary exercise testing					
Variable	Normal	Cardiov. disease	COPD	Pulm. Vasc. disease	Neurom. disease
VO_2, max	Normal	Decreased	Decreased	Decreased	Decreased
Heart rate reserve	Absent to small reserve (<20 bpm)	Absent to small reserve (<20 bpm)	Large (>30 bpm)	Small (20–30 bpm)	Large (>30 bpm)
VE, max/MVV (Ventilatory reserve)	<0.8	<0.8	>0.8	<0.8	<0.8
Ventilatory threshold	Present	Present	Absent	Present	Usually present
Dead space (V_D/V_T)	Decreased	Decreased	Decreased	Stable or increased	Decreased
O_2 Sat	Within normal limits	Within normal limits	Decreased	Decreased	Within normal limits
End tidal CO_2	Decreased	Decreased	Increased or stable	Decreased	Increased or stable
Reason for early termination	Lower extremity fatigue	Lower extremity fatigue	Dyspnea	Dyspnea, lower extremity fatigue	Fatigue

This heart failure patient is referred for risk-stratification purposes. He still complaints of shortness of breath with minimal exertion, despite optimized medical therapy, as well as BiV-AICD. CPET has been used, and published trials have been reported, for the stratification of heart failure patients, and in the prediction of their mortality. His oxygen uptake is low while his respiratory exchange ratio is high. This combination is rather worrisome despite no late admissions for acutely decompensated heart failure symptomatology. This particular cohort of patients is classified as "very high risk." Patients with Vo_2 below 10 ml/kg/min, especially with RER > 1.15, are at the highest risk for adverse cardiovascular events and their mortality rate is higher than any other heart failure group. Indeed, these results warrant further evaluation for more advanced heart failure therapies, i.e. ionotropes, ventricular devices, or cardiac transplantation.

In contrast, patients with Vo_2 values ranging between 10 and 18 ml/kg/min should have their minute ventilation (VE) and carbon dioxide output (Vco_2) measured for further stratification. The slope, or rate of change, of the curve between VE and Vco_2 is then estimated. If the slope is greater, or equal to 35 then the patient is considered to have a mortality similar to those with Vo_2 below 10 ml/kg/min, which would warrant re-stratification by RER determination. In turn, those with lower slope values, less than 35, are at moderate risk. Finally, if the Vo_2 is higher than 18 ml/kg/min, these patients are deemed low risk and regular follow up with their cardiologist is indicated.

Case 2

A 45 year old lady with history of pulmonary arterial hypertension (PAH) diagnosed by echocardiography and right sided catheterization (RHC) is referred for CPET evaluation prior to starting bosentan and revatio. Her right ventricular systolic pressure by 2D echo and RHC was estimated at 75 and 85 mmHg respectively. She undergoes successful initial evaluation by lower extremity ergometer, and her VO_2 is 9 mL/kg/min. The V_E/Vco_2 slope was estimated at 61.

This patient presents with an established PAH diagnosis. She is being referred prior to starting therapy for her condition. From the values obtained by echocardiography and RHC, the severity of her disease can be estimated. This is further corroborated by her low VO_2 and high V_E/Vco_2 slope, both of which are consistent with severe PAH. In fact, they are indicative of a high-risk patient, who requires aggressive expeditious intervention. There is extensive published data on the role of CPET in PAH. Serial testing is indicated after starting therapy for conditioning monitoring, and possible improvement. In patients whose CPET values trend towards normalization, so do the RHC hemodynamics, 2D echocardiography, NT-proBNP, and symptoms. While CPET has no role in the screening of this pathology as of yet, it has been suggested for high-risk patients, especially those with genetic predisposition. Neither is CPET meant to be the unique monitoring method in this patient population; however, it should be employed as another non-invasive tool, which has been extensively validated.

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Chapter 6
Pharmacologic Stress Testing

Eddy Karnabi and Robert C. Hendel

Exercise stress testing is usually the preferred stress testing modality unless the patient is unable to exercise or achieve the target heart rate response or possess contraindications to exercise. Additionally, in the presence of LBBB or ventricular paced rhythm, pharmacological stress testing is the modality of choice. Because the sensitivity of pharmacological stress ECG alone is low, a cardiac imaging modality is needed. Pharmacological stress testing is divided into vasodilator stress with the three available agents: adenosine, dipyridamole, or regadenoson or with a catecholamine, dobutamine.

Vasodilator stress is usually in combination with myocardial perfusion imaging (SPECT-single photon emission computed tomography or PET-positron emission tomography), and less frequently with coronary artery CT and cardiac magnetic resonance. Vasodilators agents exert their effects by acting on the adenosine receptors by increasing coronary blood flow and causing a hyperemic response. The rationale behind using vasodilators is due to the significant coronary artery vasodilation that results in three to fourfold increase in blood flow (Fig. 6.1). A normal coronary artery will exhibit a normal hyperemic response. In a stenotic coronary segment, relative flow heterogeneity is induced which is visualized with myocardial perfusion imaging, with a relative decrease tracer activity within the potentially ischemia zone of myocardium (Fig. 6.2).

The very short half-life of adenosine mandates that the infusion continue during the radiopharmaceutical delivery and uptake (1–2 min). However, the offset of hyperemia is also very rapid. In contrast, dipyridamole and regadenoson have a

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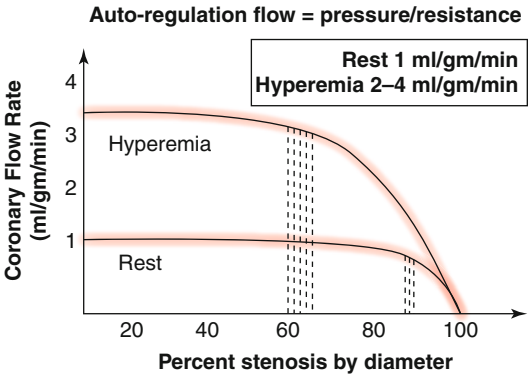

Fig. 6.1 Auto-regulation of flow in normal and hyperemic states (Adapted from Gould et al. [3]). At rest, coronary flow rate is approximately 1 ml/g/min. As coronary stenosis worsens to ~90 %, symptoms develop. During vasodilator pharmacological stress testing, coronary flow rates increase two to fourfold and coronary stenosis can be detected at 60–70 % stenosis

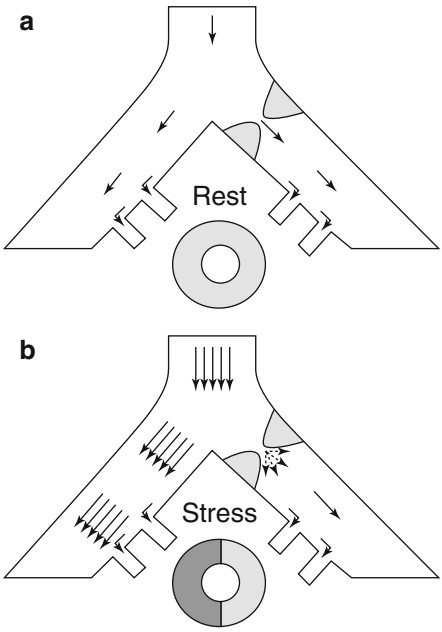

Fig. 6.2 Coronary flow in normal and stenotic arteries during rest and vasodilator stress testing. In normal state (**a**), flow distal to stenosis is compensated by vasodilation distal to the obstruction. During vasodilator stress testing (**b**), non-obstructed coronary arteries induce hyperemic response with increased flow. However, in stenotic arteries, the area distal to stenosis is already maximally dilated at rest and cannot further dilate during stress. This creates a relative hypoperfusion on MPI compared to the normally perfused myocardium

longer duration of action and may require reversal with aminophylline should side effect develop. Regadenoson is a selective A2A agonist, which limits the stimulation of non-vasodilatory receptors and reduces adverse effects. Additionally, this agent is not depend on weight based dosing.

Dobutamine is most commonly used with echocardiography but may also be used in conjunction with nuclear cardiology methods and CMR. Similar to exercise testing, dobutamine induces a positive inotropic and chronotropic response with

increase in heart rate and systolic pressure, thereby, increasing myocardial oxygen consumption and induces ischemia and wall motion abnormalities or perfusion defects in the myocardium supplied by a stenotic coronary artery.

Indications

The indications for pharmacological stress testing is similar to exercise stress testing (see Chap. 4) and according to the 2002 ACC/AHA guidelines [1] (Table 6.1).

Contraindications

All pharmacologic testing modalities should be avoided in patients with unstable clinical conditions such as hypotension, decompensated heart failure, unstable coronary syndromes or recent ACS, uncontrolled arrhythmias, and severe aortic stenosis. Absolute contraindication is hypersensitivity to any of the stress agents.

With regards to the use of vasodilator stress, the contraindications are related to the effects on the other adenosine receptors (Table 6.2).

Table 6.1 Indications for stress testing

1.	Symptoms suggestive of CAD
2.	Acute chest pain after ACS is ruled out
3.	Recent ACS not treated with coronary angioplasty
4.	Known CAD and change in clinical status
5.	Prior incomplete revascularization
6.	Newly diagnosed cardiomyopathy
7.	Certain cardiac arrhythmias: atrial fibrillation, PVCs, VT
8.	Pre-op cardiac assessment prior to non-cardiac surgery

Table 6.2 Contraindications for vasodilator stress testing [2]

1.	Asthma or COPD with active wheezing
2.	Second or third degree AV block
3.	Profound bradycardia (<40)
4.	SBP<90
5.	Use of methylxanthines (aminophylline, caffeine) in last 12 h
6.	Recent use of dipyridamole
7.	Known hypersensitivity for the stress agent
8.	Critical AS
9.	Use of regadenoson or adenosine in patients taking dipyridamol

Table 6.3 Contraindications to dobutamine stress testing

1.	Recent ACS
2.	Severe symptomatic AS (Mean PG > 40)
3.	LV outflow obstruction
4.	Arrhythmias: SVT with rapid response, hx of VT
5.	Uncontrolled hypertension
6.	Aortic dissection or large aneurysm

In cases of asthma or severe COPD with ongoing wheezing, and high degree AV block, dobutamine is an acceptable alternative. Dobutamine is a positive inotropic and chronotropic agent and should be avoided in situations where the hemodynamic effects may exacerbate existing conditions (Table 6.3).

In cases of severe hypertension and uncontrolled atrial fibrillation, vasodilator stress is an acceptable alternative. Atropine, when used in conjunction with dobutamine, should be avoided in patients with glaucoma, obstructive uropathy and prostate hypertrophy, and chronic lung disease.

Equipment

The equipment required are similar to those of exercise testing: room with a bed/stretcher, peripheral IV line, crash cart, ECG and BP recording, and an infusion pump for dobutamine, adenosine or dipyridamole. The monitor with vital signs and ECG recording is recorded every minute during the infusion and 3 min during recovery. In addition to the crash cart medications, an access to nitroglycerin, beta-blockers and aminophylline is required in case side effects and/or complications arise.

Technique

Vasodilator Stress Patient preparation includes NPO status for at least 4–6 h and avoidance of caffeine and methylxanthines for at least 24 h. A careful review of history and a physical exam is performed to detect any cardiac abnormalities such as severe AS or active wheezing. Informed consent is obtained after reviewing for appropriate indications. A peripheral IV is started and ECG electrodes connected and baseline BP recorded. ECG is reviewed to detect any contraindications for testing. Depending on the protocol, either an infusion or injection is performed (Fig. 6.3). Adenosine is given as a continuous infusion at a rate of 140 mcg/kg/min over 6 min (Fig. 6.3). The radiotracer or contrast agent is injected after 3 min. Dipyridamole is administered as 0.56 mg/kg IV over 4 min or 142 mcg/kg/min, followed by radiotracer injection after 7 min (Fig. 6.3). Regadenoson is given as a rapid injection of 0.4 mg over 10 s, followed by a saline flush (Fig. 6.3). Monitoring involves ECG recording every minute and BP every 2–3 min. If patient exhibits an adverse reaction or becomes symptomatic, either stopping the infusion (adenosine)

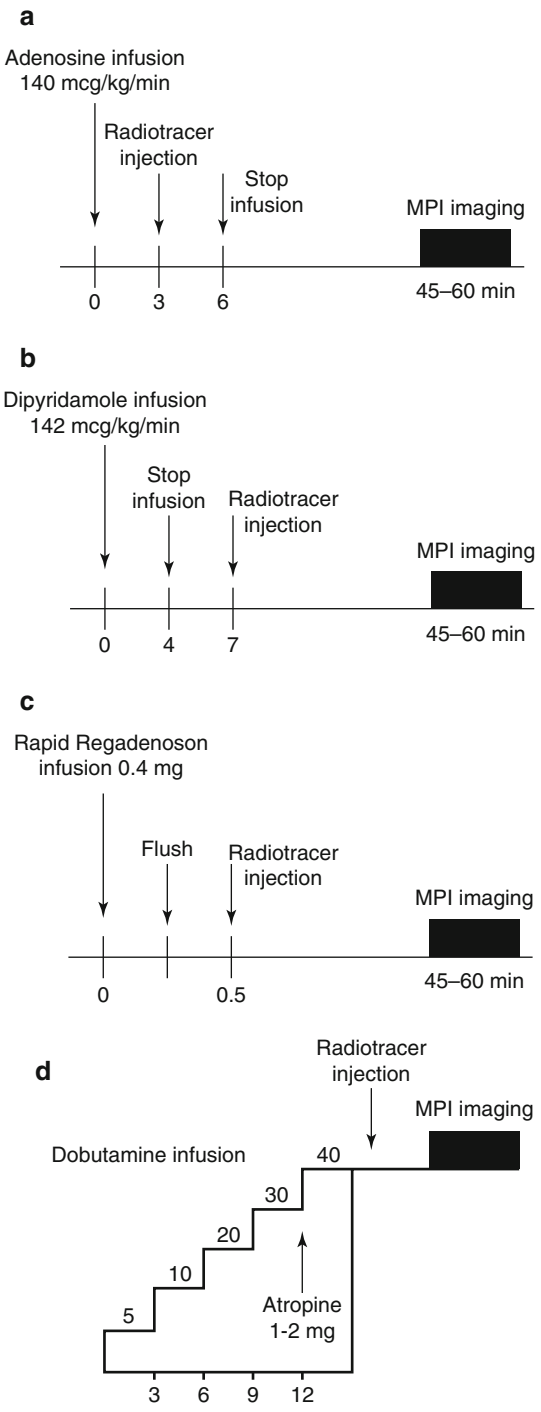

Fig. 6.3 Pharmacological stress infusion protocols [2]. (**a**) Adenosine stress infusion protocol, (**b**) Dipyridamole stress infusion protocol, (**c**) Regadenoson stress infusion protocol, (**d**) Dobutamine stress infusion protocol

Table 6.4 Indications for stopping a vasodilator

1.	Hypotension with SBP < 80 or 20 mmHg fall that is accurate
2.	ST depressions >3 mm without angina or >2 mm with angina
3.	Persistent 2nd or 3rd° AV block
4.	Severe angina, dyspnea, dizziness, headache, syncope
5.	Arrhythmias
6.	Active wheezing

or giving a reversal agent (dipyridamole, regadenoson), aminophylline 125 mg IV over 1 min should be done. Of note, aminophylline, if possible, should be delayed for at least 1-min post tracer/contrast administration to allow uptake, which will reflect the hyperemic state (Table 6.4).

Dobutamine Stress Patient preparation includes NPO status for at least 4–6 h and avoidance of beta-blockers for 24 h. A careful review of history and a physical exam is performed to detect any cardiac abnormalities such as severe AS. Informed consent is obtained after reviewing for appropriate indications. A peripheral IV is started and ECG electrodes connected and baseline BP recorded. ECG is reviewed to detect any contraindications for testing. Dobutamine is infused at gradual increasing doses from 5, 10, 20, 30, and 40 mcg/kg with the option of giving 1–2 mg atropine after 30 mcg/kg dose to achieve 85% APMHR (Fig. 6.3). The infusion should be terminated immediately with the development of unwanted effects and reversal with IV beta blockers is advised for continued ischemia.

Data Interpretation

Similar to the exercise testing, pharmacological stress testing may be reported as positive, negative or non-diagnostic ECG response depending on the ECG changes observed (see Chap. 4). Isolated pharmacological ECG testing has low sensitivity and is always combined with other forms of imaging especially with vasodilator stress.

Complications

Death and serious complications from pharmacological stress testing are very rare (<1/10,000) in the properly selected patients. Adverse effects, although common (50–75% incidence), are usually mild and bothersome but without major safety concerns. They are either self-limited and dissipate with the cessation if infusion or if intolerable, a reversal agent can be given (Table 6.5).

Combining low-level exercise and vasodilator stress reduces the side effects and enhances image quality and increases detection of myocardial ischemia. The

Table 6.5 Common adverse effects of pharmacological stress agents

Vasodilators
Flushing
Chest pain
Dizziness
Dyspnea
GI discomfort
Nausea
Headache
ST changes
AV block
Hypotension
Dobutamine
Chest pain
Headache
Palpitations
GI discomfort
Nausea
Dyspnea
ST changes
Arrhythmias
Hypertension

exceptions are left bundle branch block and ventricular paced rhythm where the increased heart rate results in artifacts.

Clinical Vignettes

Case 1

Seventy-four year old female with multiple risk factors for coronary artery disease including a strong family history, active tobacco use, diabetes mellitus, hyperlipidemia with occasional chest discomfort is sent for vasodilator pharmacological stress testing. She denied any history of COPD or cardiac conduction abnormalities. Physical exam is normal with no active wheezing. ECG at baseline was normal without ST or T wave abnormalities. Adenosine stress testing was performed. Two minutes post infusion the patient started complaining of lightheadedness; the ECG obtained is shown in (Fig. 6.4).

The patient had an adverse adenosine A1 receptor effect with complete AV block. The first step in urgent management should be immediately stopping the adenosine infusion and injecting 125 mg IV aminophylline, if the heart block per-

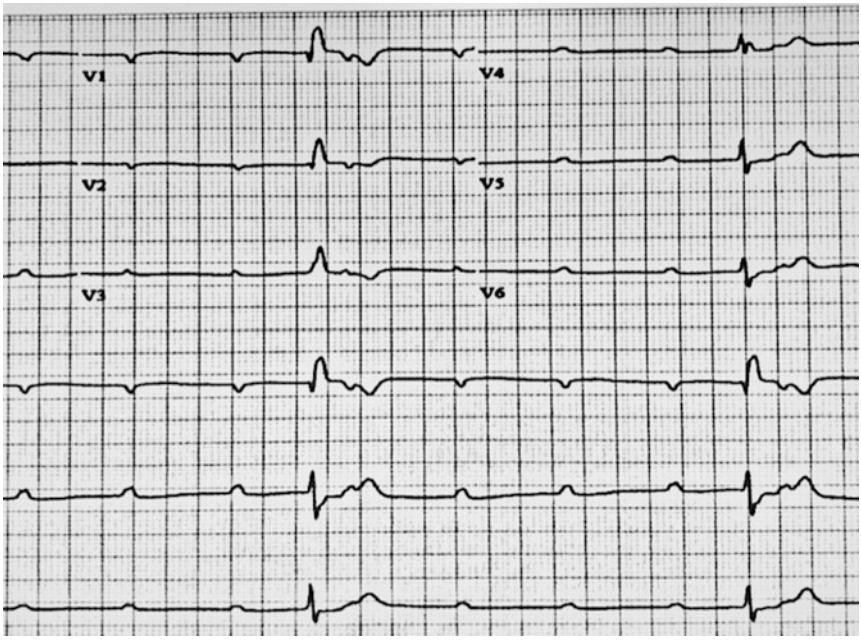

Fig. 6.4 Case #1 (see text for details)

sists. With regadenoson and dipyridamole, this adverse effect usually occurs after the stress agent administration. Thus, aminiophylline and additional patient monitoring is necessary.

Case 2

Fifty-four-year-old male with long standing history of smoking and cocaine use was admitted to the hospital with chest pain. He was ruled out for ACS and sent for stress testing. An exercise stress testing could not be performed due to lower extremity amputation. During the physical examination, he was actively wheezing, therefore, dobutamine stress test was performed. During the infusion, the patient complained of angina. An ECG is shown in (Fig. 6.5).

The ECG shows development of ST elevations during dobutamine infusion; myocardial infarction during testing is a rare side effect that should be promptly recognized and treated urgently with cardiac catheterization. The dobutamine infusion should be terminated immediately and NTG administered. Also, a beta-blocker should be given, so as to reduce the increased myocardial oxygen demand provoked by dobutamine.

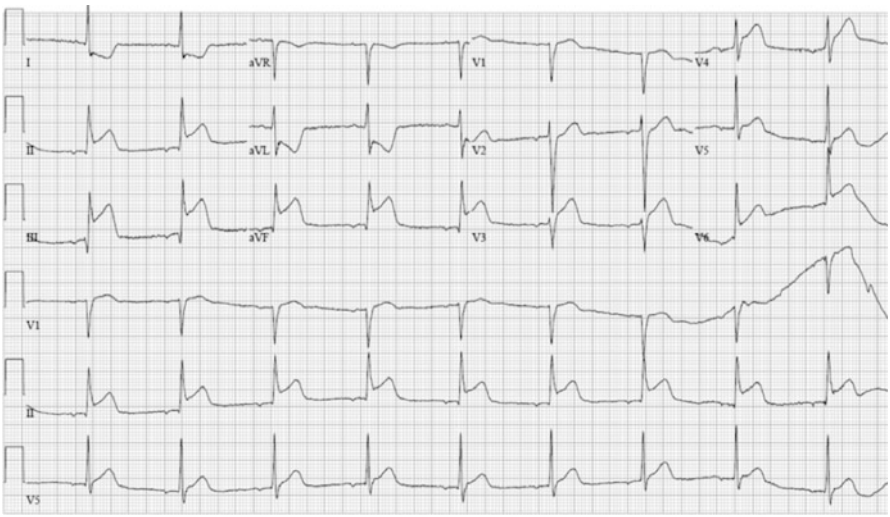

Fig. 6.5 Case #2 (see text for details)

Case 3

Sixty-four year-old female with multiple cardiovascular risk factors admitted to the hospital with atypical chest pain. After ACS was ruled out with negative cardiac biomarkers, she underwent a pharmacological stress test with regadenoson. Following the 0.4 mg IV infusion she developed flushing, dizziness and intractable headache. What is the next best step in management?

This case presents a common side effect of regadenoson which may include flushing, chest pain, dizziness, dyspnea, GI discomfort, nausea, headache, hypotension, ST changes and AV block. Ideally, for optimal tracer uptake, reversal agent's administration, such as aminophylline, should be delayed for 1 min to allow uptake by the myocardium. In this particular case, if the headache is intractable, aminophylline should be given, otherwise, mild symptoms can be treated with caffeine consumption.

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Chapter 7
Stress Echocardiography

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For more than 40 years ago, the decrease in contractile function of the heart during acute ischemia/infarction has been demonstrated with two-dimensional echocardiography and it was around the 1980s that the impact of its use with pharmacological stress became clinically obvious. Stress echocardiography (SE), is an inexpensive, relatively simple procedure with high diagnostic accuracy, that may be performed either with exercise (treadmill or bicycle) or with pharmacological stress, predominantly dobutamine.

Indications

Currently, there are about 50 indications for (SE) which can be classified into the following groups:

- Localization of coronary ischemia and diagnosis of CAD
- Prognosis and risk stratification in patients with established diagnosis
- Preoperative risk assessment

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Table 7.1 Common indications for stress echocardiography and their appropriateness [1]

Indication	Appropriate use
Evaluation of ischemic equivalent/symptoms in patient with intermediate pretest probability	Appropriate
Acute Chest pain with low TIMI score and negative troponins	Appropriate
Acute Chest pain with definite ACS	Inappropriate
Detection of CAD in an asymptomatic patient with low CAD risk	Inappropriate
Detection of CAD in patient with new-onset heart failure or left ventricular systolic dysfunction	Appropriate
Evaluation of arrhythmia without ischemic equivalent and no prior cardiac evaluation: Sustained VT, Ventricular fibrillation, frequent PVCs	Appropriate
Perioperative risk assessment for low-risk surgery	Inappropriate
Perioperative risk assessment for intermediate risk surgery in patient with moderate to good functional capacity	Inappropriate
Stress echo for risk assessment in patient within 3 months of an ACS with no recurrent symptoms and after complete revascularization	Inappropriate
Stress echo for risk assessment in patient within 3 months of an ACS to evaluate for inducible ischemia	Appropriate

- Evaluation after revascularization, both surgical and percutaneous coronary intervention
- Special subsets comprise estimation of severity of valvular disease especially in aortic stenosis, hypertrophic cardiomyopathy, pulmonary hypertension, dyspnea of suspected cardiac origin, and in patients with history of CAD scheduled for elective high-risk surgical procedures

SE is often used when the electrocardiogram (ECG) exercise stress test is non-diagnostic, and with patient who have an uninterpretable baseline ECG Table 7.1 lists some of the indications based on the 2011 Appropriate Use Criteria for Echocardiography and the 2014 Multimodality Appropriateness Criteria.

Contraindications

Contraindications for stress echocardiography are those that are present for either exercise testing (Chap. 4) or pharmacologic stress testing (Chap. 6). Absolute contraindications for cardiac stress testing include: hemodynamic instability, decompensated heart failure, acute myocardial infarction, including the presence of a new left bundle branch block, patient with acute chest pain and high pre-test probability of CAD, acute aortic dissection, high-risk unstable angina, and severe aortic stenosis symptomatic or with severe left ventricle (LV) enlargement or systolic dysfunction. Absolute indications to terminate stress testing include moderate to severe angina, sustained ventricular tachycardia, near syncope, drop in systolic pressure > than 10 mmHg from baseline in addition to other sings of ischemia [2, 3].

Relative contraindications rely on the technique and comorbidities. In about 5 % of cases, a poor acoustic window will severely limit the value stress echocardiography. A difficult resting echocardiogram serves as a cue that no interpretable results would be obtained during this test. Contrast administration should be considered for improved opacification of the LV cavity (Chap. 3). Additionally, some conditions may reduce the diagnostic accuracy of the test, including preexisting wall motion abnormalities that tether adjacent segments. Hypertrophic cardiomyopathy and other cardiomyopathies may also be problematic. Uncontrolled hypertension may also prevent attaining an adequate level of stress.

Equipment

The stress portion of this procedure may be performed with exercise or with pharmacological stressors-all required equipment should therefore be present, as outlined in previous chapters.

Ultrasound contrast agents may be needed for either with exercise or pharmacological studies and should be administered when two or more segments are not well visualized to improve accuracy by opacifying the LV and enhancing the endocardial border, and reducing the frequency of equivocal findings (Chap. 3).

A blood pressure cuff is required for registering blood pressure at rest and during every stage of the test. A 12-lead ECG should be performed at rest with monitoring throughout the examination. For the echocardiographic images, an ultrasound system that permits one to one registration of images both during rest and stress to enable concomitant comparison is necessary. A workstation is then necessary for posttest analysis and interpretation, equipped with software that allows for split and quad-screen displays for concurrent comparisons of the images at the various stages of stress. This is essential to be able to elicit subtle wall motion changes. The advances in digital imaging also allow assessing multiple cardiac cycles during stress, hence improving interpretation analysis. Image backup is should be performed. Most importantly, highly qualified professionals that are skillful in the imaging technique should perform and interpret the study.

Technique

All methods of stress testing should include standardize protocols and monitoring of vital signs at rest and during stress, rest/stress ECG. A baseline echocardiogram is performed to assess for ventricular function, chamber sizes and pressures, wall-motion thickness, aortic root, and valves morphology and functionality and to screen for contraindications for the test, significant pathology, and to ensure adequate image quality [2, 3]. If endocardial resolution is not optimal in two or more segments, then intravenous contrast enhancement should be performed as described in Chap. 3. Subsequently, left ventricle images are obtained from two parasternal

views: long and short, and apical-long axis, apical four-and two-chamber view both at rest and then at stress. Comparison of rest and stress images is performed to assess LV function and regional wall motion abnormalities.

Doppler imaging can also be performed for the measurement of pressure and flow gradients when assessing for valvular diseases and estimation of pulmonary artery systolic pressures, both at rest and peak stress.

The test is completed either by exercise-limiting symptoms or completion of the protocol, as with all forms of stress testing, but should also be terminated with the development new or worsening wall motion abnormalities (i.e., akinesis of more than two LV segments) in addition to the usual indications.

Exercise

When the choice is treadmill, imaging is usually not feasible during exercise and is actually performed immediately afterwards, aiming to complete image acquisition within 1 min from cessation of exercise. This assumes that the ischemia will persist for at least that time; hence if it recovers rapidly, false-negatives occur. The patient must be rapidly transferred from the treadmill to the appropriate supine position. This requires patient cooperation and a well-coordinated approach by staff. If a stationary bike is used, workload is increased every 2–3 min and images in this case are obtained at peak stress. Although true stress images may also be obtained with treadmill exercise, this method is challenging and infrequently performed.

Pharmacologic Stress Testing

Dobutamine is the preferred pharmacologic stress agent for stress echocardiography (Chap. 6). It is performed on a continuous infusion beginning at 5 μg/kg/min, with increasing dosages to a maximum of 50 μg/kg/min; if target heart rate not is achieved, atropine may be used in doses ranging from 0.25 to 0.5 mg to a total of 2.0 mg [1, 2, 4]. Image acquisition should occur at baseline and for each level of dobutamine stress. Ideally, the peak stress images should be obtained after the target heart rate is achieved.

Data Interpretation

Grading of each of the 16 segments is performed at rest and with stress both at low and intermediate stages and described as normal, hyperdynamic, hypokinetic, akinetic, dyskinetic, or aneurysmal. Timing of wall motion is also considered. Table 7.2 shows the interpretation of regional wall motion abnormalities based on findings at rest and during stress.

Table 7.2 Interpretation of regional wall motion abnormalities [5]

Rest	Stress	Interpretation
Normal wall motion & Contractility	Hyperdynamic	Normal
Normal wall motion	New wall motion abnormality or lack of hyperdynamic wall motion	Ischemia
Wall motion: Hypokinesis	Worsening hypokinesis akinesis or dyskinesis	Ischemia
Wall motion: Hypokinesis	Unchanged	Infarction
Akinetic	Improved to hypokinesis or to normal wall motion (Biphasic response)	Viable (Hibernating) Myocardium

Adapted from Oh et al. [5]

The final report must include all the protocol information, vital signs, heart rate achieved and blood pressure response, level of stress tolerated and its adequacy, doses of the medications that were used, changes in ECG, presence or absence of symptoms, systolic function and wall motion description.

Complications

Life threatening complications including asystole, acute myocardial infarction, sustained ventricular tachycardia, pulmonary edema or sudden cardiac death do occur be in less than 1/1000 [2]. However, "bothersome" side effects do occur, as noted in Chaps. 4 and 6.

Clinical Vignettes

Case 1

A 62 year-old woman was brought to the Emergency Department with a 8-h history of atypical chest pain that began when she was notified that her husband was in a car accident and in critical condition. The chest pain had resolved spontaneously. She had history of dyslipidemia, hypertension, and diet-controlled diabetes mellitus. Initial ECG demonstrated very mild ST- elevation in V1-V3 and troponins were negative. As part of her initial work-up, she underwent e echocardiography.

Figure 7.1 demonstrates a positive stress echo study showing images at rest (a) and stress (b). During stress, there is marked akinesis and ballooning of the apex, apical anterior/lateral/septum and inferior. The patient underwent a cardiac catheterization that showed normal coronaries consistent with apical ballooning/ Takotsubo's cardiomyopathy.

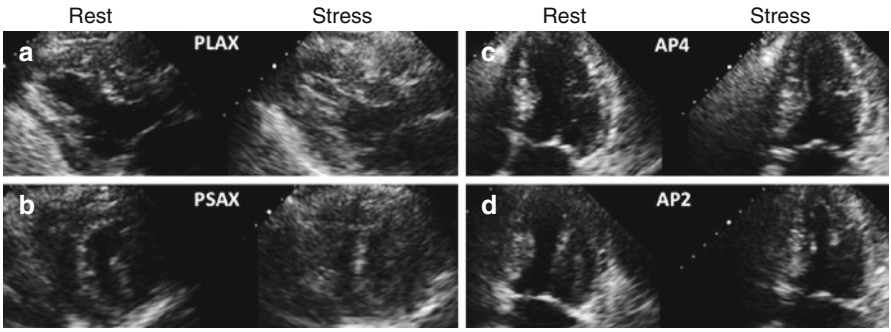

Fig. 7.1 Case #1 (see text for details)

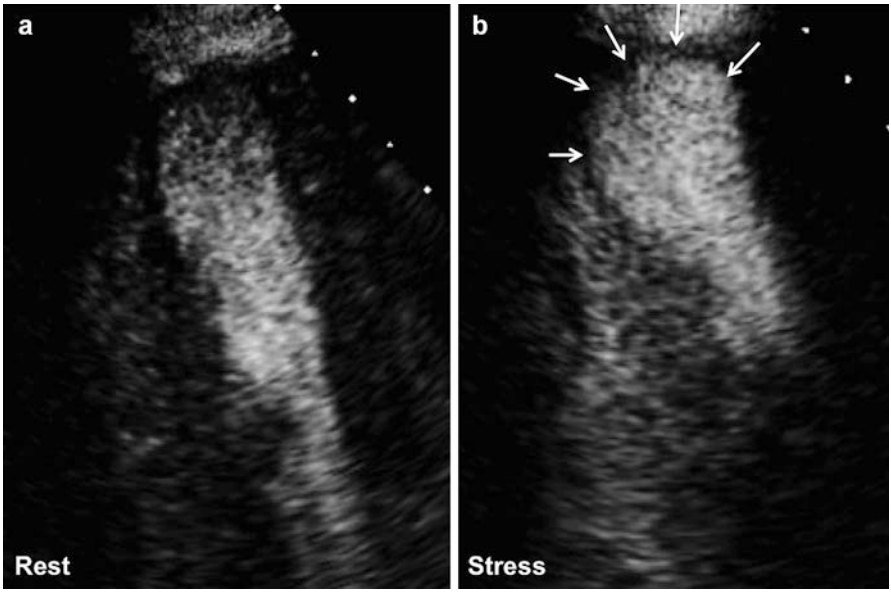

Fig. 7.2 Case #2 (see text for details)

Case 2

A 55 year-old male with presented with history of atypical chest pain that had resolved upon arrival to the Emergency Department. He had a past medical history of well-controlled HTN and dyslipidemia and no previous cardiac history. ECG demonstrated LVH but no acute ST-T wave abnormalities. Troponins were negative. Given intermediate pretest probability for CAD and uninterpretable ECG, he underwent exercise echocardiography (Fig. 7.2). *He completed 12 min of a Bruce protocol, achieving a heart rate of 92 % of the maximum predicted heart rate. There was an additional 2 mm horizontal ST depression with exercise, but the patient did not develop chest pain.*

The stress echo was normal. Panels A-D show Parasternal long axis (PLAX), Parasternal short axis (PSAX), Apical 4 chamber (AP4) and Apical 2 chamber (AP2) acquired at end systole during rest and peak exercise. Note the normal systolic excursion/wall motion and thickening during peak exercise. The ST segment response to exercise was a false-positive result, likely related to the baseline ECG abnormalities.

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Chapter 8
Single Photon Emission Computed Tomography

Eddy Karnabi

Single-Photon Emission Computed Tomography (SPECT) is the most widely used nuclear imaging technique in cardiology, playing an important role in the detection of coronary artery disease (CAD), viability assessment, and risk stratification. Myocardial perfusion imaging (MPI) improves the sensitivity and specificity over standard exercise stress testing and provides information regarding systolic function and wall motion abnormalities with gated SPECT.

Indications

According to the appropriate use criteria [1] (Table 8.1).

Contraindications

The contraindications to the use of exercise and pharmacological (adenosine, dipyridamole, regadenoson, dobutamine) stress testing are presented in previous chapters. The contraindications specifically for nuclear cardiology include patients who received iodine I-131 therapy within 12 h or technetium-99 studies within 48 h. In addition, due to the radiation exposure, SPECT is contraindicated in pregnancy and breast-feeding. Finally, uncooperative patients who are unable to lie supine for at least 30 min are not encouraged to undergo the procedure. In rare instances, it is contraindicated if there is an allergic potential to the radiopharmaceutics.

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Table 8.1 Appropriateness use criteria for SPECT

1	Acute chest pain (or ischemic equivalent) after definite ACS is ruled out
2	In chronic stable chest pain, patients with intermediate to high pretest probability or low pre-test probability in which the ECG is un-interpretable and unable to exercise
3	In asymptomatic patients, patients with high CHD (defined by >20 % 10 year risk)
4	In asymptomatic patients with new cardiomyopathy and a depressed systolic function with no prior CAD evaluation
5	Patients with arrhythmias such as VT or new onset atrial fibrillation
6	Patients with elevated cardiac enzymes without evidence of ACS
7	Patients have an abnormal prior stress testing and present with new or worsening symptoms
8	Pre-operative evaluation in intermediate risk population or if undergoing vascular surgery if functional capacity can not be assessed or is poor and if there is one or more risk factors for CAD.
9	In post-revascularization patients who are symptomatic or were incompletely re-vascularized
10	Asymptomatic or symptomatic CABG patients if performed >5 years prior, (Uncertain indication in asymptomatic patients >2 years post PCI)
11	Myocardial Viability study using Thalium-201 or technetium 99m radiotracer in combination with SPECT as an alternative to other imaging modalities to asses viability

Equipment

The essential tool for performing a SPECT study is the gamma or scintillation camera that detects the gamma rays (photons) produced from the injected radiopharmaceutical agents [2].

A gamma camera consists of a single crystal, usually sodium iodide crystal (NaI), a collimator, and photomultiplier tubes (PMT). The NaI crystal is able to scintillate when subjected to ionizing radiation in form of photons. The collimator is designed to limit by attenuation, the detection of gamma rays to those traveling in certain directions. The photomultiplier tubes convert photon energy and scintillation within the crystal into electrical energy that is processed by the pulse height analyzer. The energy spectrum obtained consists of a photopeak and multiple Compton scatters. Only signals in the specific energy range of the radiotracer (the photopeak) are processed and the counts analyzed.

The basic components of the gamma camera have not changed much over the years except for upgrading from scintillation detectors to semi-conductor detectors such as Cadmium Zinc Telluride (CZT) detectors with improved count detection and thus images.

The radiopharmaceutical tracers [3] used are thallium-201 and technetium-99m based agents, Tc-99m sestamibi and Tc-99m tetrofosmin, Due to the energy spectrum, effective half life and more favorable dosimetry, the technetium agents are preferred for gated SPECT imaging. These agents emit photons with a single photopeak of 140 keV and have a half-life of 6 h. After injection, 40–60 % is extracted by the myocardium and myocardial washout/redistribution is minimal requiring two injections at rest and peak exercise.

Technique

After performing an exercise or a pharmacological stress test and the injection of the pharmaceutical radiotracer, images are obtained. The images obtained by gamma cameras are 2 dimensional (2D) images of a 3 dimensional (3D) object. Multiple 2D planar projections are acquired from multiple angles to reconstruct a 3D image using a reconstruction algorithm.

Imaging times post injection for technetium-based agents, scanning can start 15–20 min after exercise and 45–60 min after rest or pharmacological stress testing. The routine position to acquire images is supine with arms above the head. In cases of significant inferior wall attenuation, the addition of prone images helps eliminate the inferior wall attenuation, creates more uniform breast attenuation, less motion artifact, but may cause an artifactual anteroseptal defect. The gamma camera is placed as close to the patient as possible for improved resolution with either one of the orbital types: circular or non circular (elliptical or body contour). In a double headed camera, planar images are obtained in a 180° arc that extends from 45° right anterior oblique (RAO) to 45° left posterior oblique (LPO). The acquisition type could be a "step and shoot", continuous, or continuous "step and shoot". For a dual head camera, low dose studies usually takes 25–30 s/step and for high dose studies 20–25 s per step which translates to approximately 12–16 min total time for the study. Using a single head camera will yield double the time to acquire the images.

Hybrid SPECT-CT systems are in use and play an essential role in attenuation correction.

Radiopharmaceutical protocols [3]:

1. One day dual isotope (discouraged and less widely used due to the high radiation exposure)
2. Two day technetium based tracer
3. One day single isotope (Rest-stress or stress-rest)
4. Stress only imaging with ECG gated SPECT and validated attenuation correction
5. One day stress-delay thallium imaging for viability

Single isotope usually technetium based one day protocol is the most widely used. A rest injection is performed with low dose 8–9 mCi followed by SPECT imaging 45–60 min afterwards. After a 3-h delay, stress testing is performed and high dose 25–30 mCi is injected followed by SPECT imaging 15–30 min for exercise and 45–60 min for pharmacological stress testing (Fig. 8.1). The advantages of a single day protocol is good validation, fast tract protocol, easier image interpretation, able to determine transient ischemic dilation (TID), and validated attenuation correction. The 2-day protocols advantage is high quality rest and stress images as a result of using high dose injections with rest and stress. This is beneficial in an obese patient but requires 2 days to complete the study. More recently, stress only images are being performed; if SPECT images are normal, the rest images are not required.

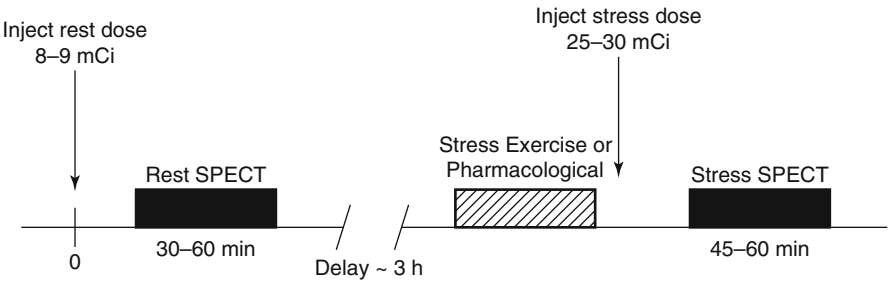

Fig. 8.1 Typical 1-day rest-stress technetium protocol. Rest dose of 8–9 mCi is injected followed by rest SPECT images 30–60 min. After a delay of approximately 3 h, the stress portion is performed followed by stress tracer injection of 25–30 mCi. After 15 min for exercise or 45–60 min for pharmacological stress testing, the stress SPECT images are obtained

For SPECT viability studies, thallium-201 2.5–3.5 mCi is injected followed by rest images at 15 min post injection. Redistribution images are delayed 4 h to detect viable myocardium. Further delayed or late redistribution mages can be obtained 24 h post injection as well.

Data Interpretation

The radiotracer is distributed throughout the myocardium, however, more predominantly in the left ventricle. The standard SPECT views include the short axis from apex to base, vertical long axis, and horizontal long axis (Fig. 8.2). Data interpretation involve following a review sequence as outlined by the ASNC guidelines [4] and involves: examining the unprocessed images for image quality, artifacts such as motion artifacts (vertical or horizontal), breast or subdiaphragmatic artifacts, extracardiac uptake, and increased lung uptake, followed by examining for perfusion abnormalities fixed or reversible between rest and stress images, examining the polar map or bulls eye, and examining the gated SPECT images for wall motion abnormalities and ejection fraction.

As coronary flow decreased due to coronary obstruction, less radiotracer uptake occur which translates to lower count on the perfusion images. Defects can be reversible or fixed. Fixed defects are areas with absent tracer uptake on both rest and stress images. Fixed defects represent a scarred or infarcted myocardium or a viable hibernating myocardium. Differentiating a scarred myocardium from a viable myocardium requires either thallium-201 SPECT redistribution viability study or PET based study. Reversible defects are defined as normal perfusion images at rest but with decreased uptake on stress images; this pattern is consistent with ischemia.

The ischemic myocardium can usually be traced to a coronary distribution Left anterior descending (LAD), Circumflex (Cx), or Right coronary artery (RCA) (Fig. 8.3) unless multiple territories are involved. Quantitative analysis is performed by comparing count densities from the stress using the short axis images with a

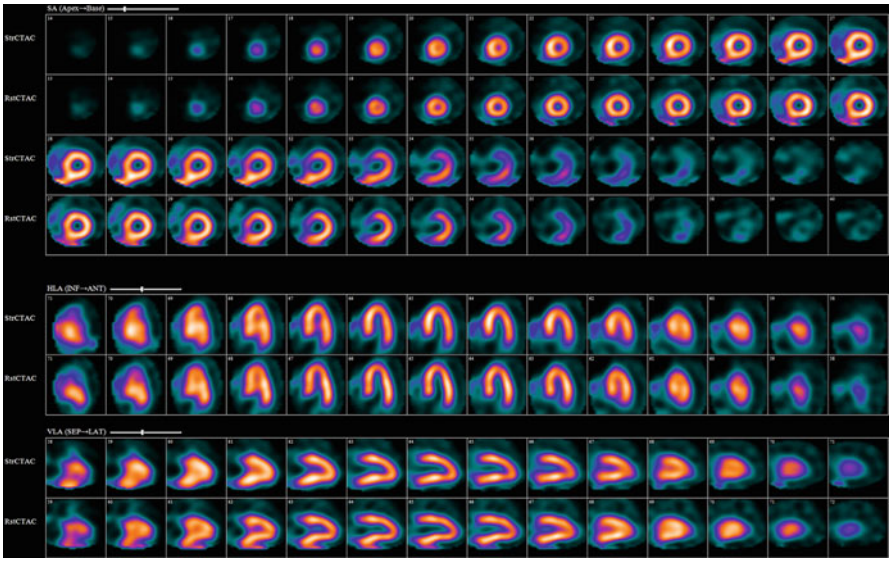

Fig. 8.2 A normal myocardial perfusion imaging showing the short axis from apex to base (usual presentation is stress images on top and rest images on bottom), horizontal long axis showing septum and lateral walls, and vertical long axis showing the anterior and inferior myocardium

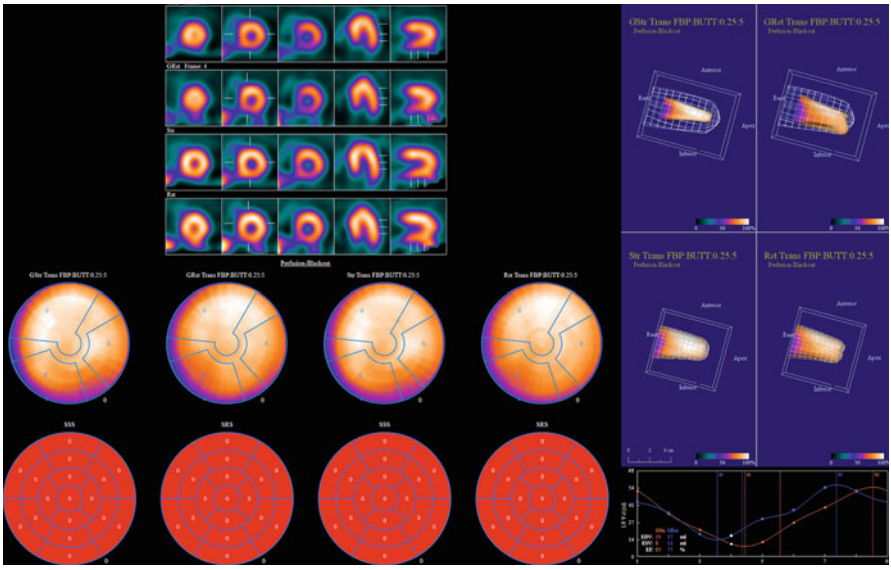

Fig. 8.3 A polar plot or bulls eye with semiquantification using the 17-segment model. The LAD (left anterior descending) territory is between 9 and 1 O'clock, Cx (Circumflex) territory between 5 and 8 O'clock, and RCA (right coronary artery) territory between 2 and 5 O'clock. On the left, gated SPECT images are shown during diastole (*bottom*) and systole (*top*)

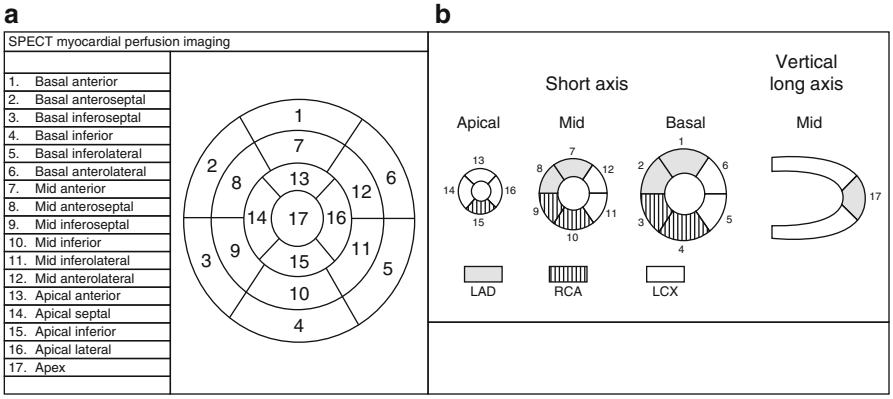

Fig. 8.4 SPECT myocardial perfusion imaging showing the 17-segment model and Coronary distribution (Adapted from the Cerqueira et al. [5]). *LAD* left anterior descending artery, *RCA* right coronary artery, *LCX* left circumflex artery. (**a**) indicates terminology of each of the 17 segments and there location on a polar map. (**b**) depicts the location of the segments on short axis and vertical long axis views and the empirically allocated vascular territory

Table 8.2 The five point model

Normal perfusion	0
Mild decreased counts	1
Moderate decreased counts	2
Severe decreased counts	3
Absent uptake	4

Table 8.3 Semiquantitative defect analysis

	Number of segments	Percent of LV
Small	1–2	5–10
Moderate	3–4	15–20
Large	>5	>20

normal count profile from a cohort of normal patients. A bulls eye or a polar map is displayed (Fig. 8.3), however, this method should only be used in conjunction with visual analysis. Using the 17-segment model (Adapted from Cerqueira et al. [5]) (Fig. 8.4), a score may be given to each segment (Table 8.2).

Three scores are obtained: SRS summed rest score; SSS summed stress score and SDS summed difference score (SDS = SSS−SRS). The SRS shows the extent and severity of infarction, SDS extent and severity of ischemia, and SSS extent and severity of both ischemia and infarction (Table 8.3).

Similarly, the percent LV myocardium involved can be calculated by number of segments affected divided by 68 (4 points per each segment multiplied by 17 segments) × 100.

An important part in interpretation is the detection of transient ischemic dilation (TID). TID is most likely due to diffuse subendocardial ischemia. It is calculated by dividing Stress EDV (End-diastolic volume)/Rest EDV. Cutoff value of >1.22 for dual isotope and >1.12 for single isotope studies is considered significant. However, the threshold is higher for pharmacological stress testing >1.36 since the physiology

in vasodilator stress is to redirect perfusion away from the endocardium. TID in combination with an abnormal perfusion images signifies extensive CAD either multi-vessel disease or proximal LAD disease and correlates with worse prognosis. However, TID in combination with normal perfusion images has low specificity for multi-vessel disease and is not associated with adverse prognosis. This is usually encountered in patients with significant left ventricular hypertrophy (LVH) especially with a hypertensive response that results in subendocardial ischemia from the thick ventricular walls.

Gated SPECT imaging improves the specificity of MPI by differentiating a fixed defect from an infarction/scar and an artifact. Wall motion abnormalities can be detected as well as an estimation of systolic function and an ejection fraction (EF).

Artifact recognition is an important part of SPECT imaging and include instrumentation-related artifacts (center-of–rotation, non-uniformity etc.) and patient-related artifacts (patient motion, attenuation, etc.).

Finally, the report should not only describe the clinical indication, the technical features of the examination, and the imaging results but also include the impression whether the study is normal or abnormal and addressing the perfusion abnormalities by noting the size, severity and location of each abnormality. Recognition of artifacts if present, addressing regional or global wall motion abnormalities with estimation of EF, inclusion of ECG findings, and integration with the clinical information to address the indication of the study.

Complications

The complications to myocardial perfusion imaging are related to the radiation exposure both to the patients and to the staff. Ionizing radiation has been linked to solid cancers and leukemia. Hence, the principle of ALARA (As low as reasonably achievable) applies.

Clinical Vignettes

Case 1

Sixty year old male with multiple risk factors for CAD including hypertension, hyperlipidemia, and extensive tobacco history with limited functional status due to claudication for over the past year and significant vascular disease involving the femoral artery is referred for a pharmacological stress test myocardial perfusion imaging prior to vascular surgery. The MPI images are shown in Fig. 8.5.

This case shows a normal myocardial perfusion imaging during rest and stress with a normal bulls eye or polar plot. His annual event rate is less than 1 % and he should be able to proceed with the planned vascular bypass surgery.

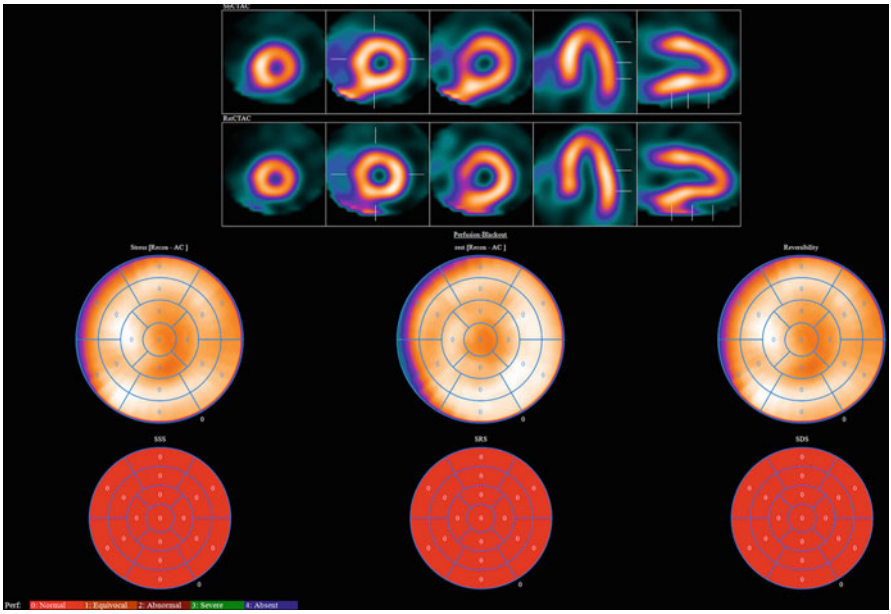

Fig. 8.5 Case #1 (see text for details)

Case 2

Seventy-eight-year-old male with hypertension, CAD with prior myocardial infarction was admitted to the hospital with chest pain. A myocardial perfusion stress testing was performed with images shown in Fig. 8.6.

This case presents a patient with a prior MI in the LAD and RCA territories and evidence of a small amount of peri-infarct ischemia in the anterior wall.

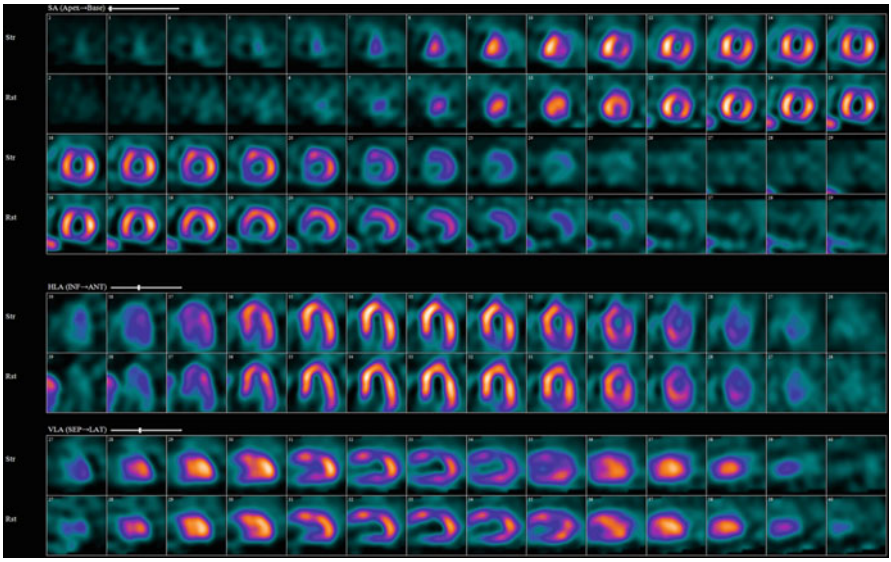

Fig. 8.6 Case #2 (see text for details)

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Chapter 9
Positron Emission Tomography

Eddy Karnabi

Positron emission tomography (PET) imaging has increased substantially in recent years. PET allows noninvasive evaluation of myocardial blood flow, function, and metabolism. The advantages of cardiac PET imaging over SPECT are [1]: improved image quality (especially in obese patients) with high both temporal and spatial resolution, relatively short imaging protocols, routine attenuation correction (depth independent), providing peak stress ejection fraction (EF)-no time delay between hyperemic response and imaging and true quantification of myocardial blood flow and myocardial metabolism. In addition, PET provides equal sensitivity with higher specificity and diagnostic accuracy compared to SPECT. However, cardiac PET still faces the challenges of being less available, with a greater cost, less expertise, challenges of performing exercise stress due to the short half-life of the currently available radiotracers making pharmacological stress testing the only current option (until the availability of new radiopharmaceutical agents), and reimbursement issues.

Indications

The indications for cardiac PET [2, 3] are similar to those for cardiac SPECT in term of myocardial perfusion imaging for the diagnosis and risk stratification of CAD. However, its role is extended to patients with an equivocal SPECT. In addition, cardiac PET is used as a viability study in patients with ischemic cardiomyopathy. Recently, there has been an increased use in heart failure and in the identification of cardiac sarcoidosis (Table 9.1).

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Table 9.1 Indications for positron emission tomography

1	Intermediate likelihood of CAD and/or risk stratification in patients with intermediate and high likelihood of CAD when
	Equivocal SPECT Unable to exercise Able to exercise but ECG with LBBB or ventricular paced rhythm
2	Evaluation of myocardial viability
3	Evaluation of heart failure (Cardiac Sarcoidosis)
4	Quantification of myocardial blood flow

Contraindications

The contraindications to cardiac PET are similar to SPECT (Chap. 8), which include the standard contraindications to pharmacological stress testing when PET perfusion imaging is being done. Inability to lie flat or lie still for the period of acquisition, claustrophobia and extreme weight (>350–400 lbs.) are usually preferred not to undergo PET imaging. Finally, women who are pregnant or breast-feeding are contraindication.

Equipment

The equipment required for a standard cardiac PET examination includes the radionuclides and the PET camera, mostly as a hybrid (with CT) unit. The radionuclides used for PET imaging have a considerably shorter half-life as compared to SPECT tracers. PET radionuclides are produced either from a cyclotron such as fluoro-2-deoxyglucose F-18 FDG and N-13 ammonia or a generator such as rubidium Rb-82. As the name implies, PET imaging involves a positron that collides with an electron to produce two 511 keV gamma rays/photons emitted collinear to each other at 180° angle. The PET detectors are configured to only register the photon pairs if they strike opposite detectors at approximately the same time that has been termed the coincidence detection. The summations of multiple coincidence events are used to reconstruct the PET image to be used for analysis.

The CT scanner provides addition information such as coronary artery calcium scoring and/or noninvasive coronary angiography, but more importantly for PET imaging is in registration and attenuation correction.

The PET camera, similar to SPECT, is made of multiple small detector crystals arranged in a 360° ring and photomultiplier tubes to convert the scintillation events to electrical signal and digitalization to provide the counts that are used in quantification and image processing. Three types of detector crystals are available: (1) Bismuth germanate (BGO) (2) Lutetium oxyorthosilicate (LSO) (3) Gagolinium oxyorthosilicate (GSO).

The clinically available PET tracers for myocardial perfusion studies are Rb-82, and N-13 ammonia. Figure 9.1 shows the radiotracers myocardial uptake

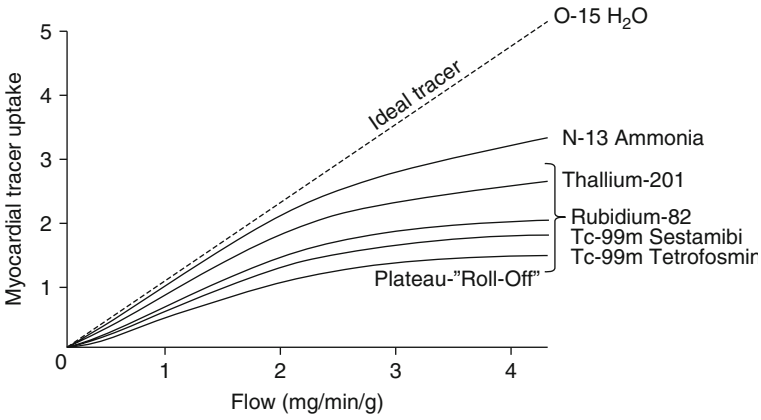

Fig. 9.1 Relationship of the myocardial uptake of the radiopharmaceutical to blood flow. O-15 water is the ideal tracer

Table 9.2 PET radiotracers

Myocardial perfusion	Myocardial metabolism
Rubidium-82	F-18 = Glucose metabolism
Ammonia N-13	C-11 acetate = Oxidative metabolism
Water O-15	C-11 palmitate = fatty acid metabolism
F-18 agent	

in relation to coronary blood flow with O-15 being the ideal tracer and the roll-off phenomenon seen with other tracers at higher coronary blood flows. N-13 ammonia, due to the short half-life (10 min), requires an on-site (nearby) cyclotron. It has excellent myocardial uptake/retention with established flow quantification and applications in exercise and pharmacological stress testing. Rubidium-82 is produced on-site from a Strontium-82 generator (replaced every 4 weeks) with a half-life of 76 s. Due to the short half-life, it can only be used in pharmacological stress testing. It has with high extraction at high flows (enhances the detection of moderate-severe CAD). Rb-82 is extracted by myocardial cells via the Na/K ATPase pump. The radiation dosimetry from Rb-82 varies from 1.75 to 7.5 mSv total effective dose. Depending on the left ventricular ejection fraction, typically imaging can commence 70–90 s after the injection if LVEF >50 % and delayed slightly longer (~110 s) if LVEF <50 %.

For metabolism imaging, the F-18 FDG tracer (the only FDA approved agent), an analog to glucose, is used. F-18 is produced in a cyclotron and decays with a half-life of 110 min, which allows sufficient time to be produced and distributed in a radius of several hours from the production site. FDG is transported into the cells similar to glucose and is then phosphorylated by hexokinase to FDG-6-phosphate, which is then trapped in the myocardium for PET imaging. The whole body dosimetry from 10 mCi dose is 7 mSv (Tables 9.2 and 9.3).

Table 9.3 Properties of PET radiotracers

	Tracer	Production	Half-life	Compound	Uptake/ metabolism	Positron range (mm)	FDA approval
Perfusion	O-15	Cyclotron	2.1 min	H_2O	Freely diffusible	0.36	×
	N-13	Cyclotron	10 min	NH3	Extraction Na/K ATPase	0.28	√
	Rb-82	Generator	76 s	RbCl	Extraction K channels	1.6	√
Metabolism	C-11	Cyclotron	20.4 min	Acetate, Palmitate	Active extraction	0.22	√
	F-18	Cyclotron	110 min	Deoxyglucose	Glucose transporter	0.18	√

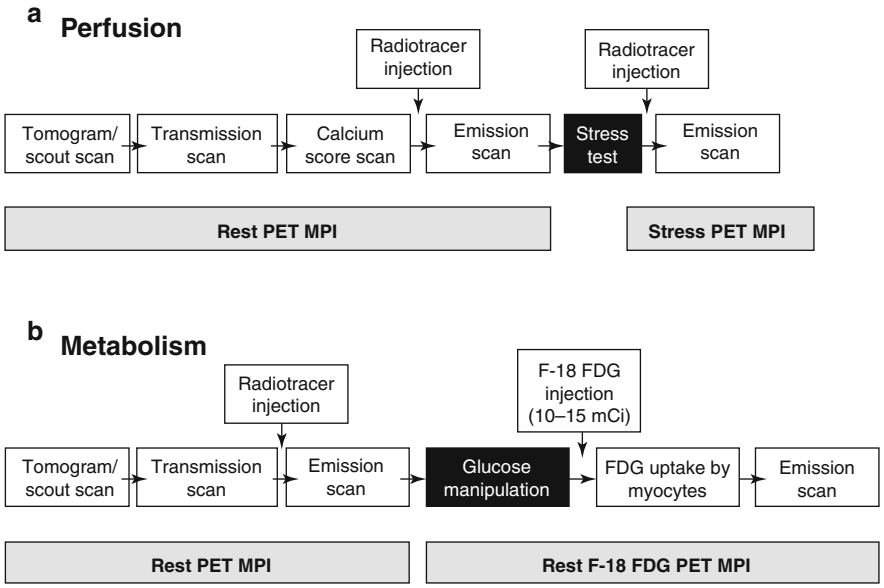

Fig. 9.2 Sample PET protocols for myocardial perfusion (**a**) and metabolism/Viability (**b**)

Technique

Patient preparation for pharmacological stress testing and myocardial perfusion imaging is similar to what was previously described in the previous Chap. 6 (Pharmacologic Stress) and 8 (SPECT). For myocardial perfusion imaging (Fig. 9.2), an overnight fast of at least 6 h is required. Following the stress portion, Rb-82 or N-13 is injected at peak hyperemia through a peripheral IV line and emission scans are performed.

Viability studies require a specified protocol for glucose manipulation. In order to allow the myocardium to utilize glucose, an overnight fast of at least 6–12 h (Step1) is required as patient metabolic preparation is key to successful F-18 FDG imaging to assess viability. The most common metabolic preparation for viability imaging is the use of an oral load of glucose 25–100 g (Step 2) followed by supplemental IV insulin (Step 3) as needed.

The imaging parameters include patient positioning supine with the arms raised above the shoulder level. To localize the heart within the field of view (FOV), a tomogram or scout CT is performed followed by a transmission scan for attenuation correction. Rest or stress emission scans are then performed. For the FDA approved radiotracers, the dose used are: for Rb-82 is 40–60 mCi, N-13 ammonia 10–20 mCi, and for F-18 FDG 5–10 mCi. The scan duration for Rb-82 is 3–7 min, N13 ammonia 10–15 min, and for F-18 FDG 10–30 min.

Of note, rest-stress MPI and viability PET protocols (Fig. 9.2) may be combined to provide information on both ischemia and viability.

Data Interpretation

As outlined by the ASNC guidelines on radionuclide imaging [4], the sequence involves analyzing the raw images, followed by assessment of perfusion abnormalities, evaluation of gated images for left ventricular function, quantification of myocardial blood flow. In addition, with hybrid PET/CT scans, coronary artery calcium and/or coronary CT angiography may be included in the report. Non-cardiac findings should be reviewed and mentioned such as pleural or pericardial effusions, aortic disease and calcifications, mediastinal or lung masses or nodules. The rest and stress perfusion images and metabolism images should be analyzed for the extent and severity of abnormalities. Extra-cardiac findings should be carefully examined for uptake in organs other than the myocardium particularly the lungs and the mediastinum. Similar to SPECT imaging, PET images are presented in short axis from apex to base, horizontal long axis with septal and lateral walls, and vertical long axis showing the anterior and inferior walls. Interpretation of PET perfusion data (similar to what is described in Chap. 8) should be performed visually/qualitatively first with identification of location and defect severity and extent. The extent can be qualitatively described as small (5–10 % of the LV), medium (10–20 % of the LV), or large (>20 %) of the LV. Defect severity is expressed as mild, moderate, or severe. Myocardium with stress induced perfusion abnormalities, which have normal stress imaging represent ischemia. Perfusion abnormalities present both at rest and stress i.e. fixed defects represents an area of scan or infarction. The 17-segment model with the 5-point scale (Fig. 8.4) is used for the semi-quantitative analysis as outlined in the SPECT chapter.

Absolute quantification of myocardial blood flow is an important aspect of PET imaging that helps in assessing the physiological significance of a known coronary artery stenosis especially if it is in the intermediate range. Both relative and absolute

quantification is possible. Quantitative assessment of blood flow is in ml of blood per min per gram of myocardium and is validated for N-13 and Ru-82.

ECG Gated PET images at rest and peak stress provides information on LV function and volumes. Unlike post-stress SPECT, PET images are obtained at peak hyperemia and stress. Regional and global wall motion abnormalities can be identified.

Assessment of myocardial viability plays a central role in PET imaging. Viability studies are able to differentiate a scarred or infarcted myocardium from a hibernating myocardium, which upon revascularization might restore LV function. Rest perfusion imaging is compared to metabolism imaging using FDG uptake (Fig. 9.3). A myocardial perfusion abnormality in combination with no FDG uptake signifies an infarcted and scarred myocardium. An increase in FDG uptake relative to a perfusion abnormality i.e. a mismatch signifies a viable myocardium (Table 9.4).

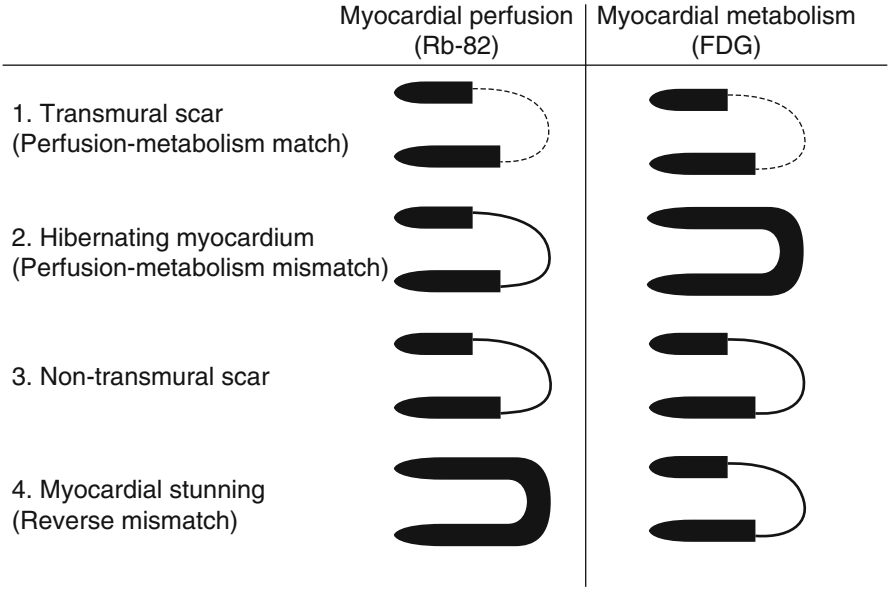

Fig. 9.3 Myocardial perfusion and metabolism patterns

Table 9.4 Myocardial perfusion and metabolism patterns

	Myocardial blood flow	Myocardial FDG glucose loaded	Regional function
Normal	Normal	Normal	Normal
Hibernating	↑	↓	↑
Transmural scar	↑	↑	↑
Non-Transmural scar	Partially ↑	Partially ↑	↑ /Normal
Stunning	Normal	↓ / ↑	↑
NICMP	Normal	Normal	↑

NICMP non ischemic cardiomyopathy, *FDG* fluorodeoxyglucose, ↓ / ↑ increase/decrease

The standard reporting algorithm of myocardial perfusion and metabolism PET studies includes: patient information, indication for the study, history and key clinical findings, type of the study, summary of stress data with stress ECG interpretation, image description and interpretation for perfusion and metabolism, and final impression whether the study is normal or abnormal.

Complications

The complications to pharmacological stress perfusion imaging are presented elsewhere. The risk of PET imaging include radiation exposure and risk of solid cancers and leukemia due to stochastic effects of ionizing radiation. For instance, the total body effective dose of radiation exposure from a myocardial perfusion using Rubidium RB-82 is approximately 4.1 mSv and from F-18 fluorodeoxyglucose myocardial viability scan is approximately 7.0 mSv. In order to prevent or limit the effects of ionizing radiation, the principle of ALARA (As low as reasonably achievable) should be followed. Hence, appropriate indications for testing should be followed per the ACC/AHA and ASNC appropriate use criteria. Once a proper indication is confirmed, it is important to limit the amount of radiation and to use the lowest possible dose of radioisotopes to obtain accurate images for interpretation.

Clinical Vignettes

Case 1

Seventy-two year old man presents with mild stroke and chest pain. History includes smoking (*50 pack year*), *elevated cholesterol*, *diabetes. During hospitalization*, *the resting ECG demonstrated mild inverted t-waves and TnI elevation*, *also mild. The patient was obese*, *BMI 35. The patient underwent a rest/stress dipyridamole PET study with mild chest pain but no ECG changes. Images are shown in* Fig. 9.4.

There was TID and two separate perfusion abnormalities. There was a medium moderate/severe completely reversible antero/lateral and inferolateral defect as well as medium moderate/severe reversible anteroseptal, apical and inferoseptal defect confined to the apical regions. These findings were consistent with 2 vessel ischemia, circumflex and left anterior descending arteries. The patient underwent coronary catheterization which showed LAD which was occluded in the mid region, a ramus with 60–70 % stenosis and circumflex proximal 90 % stenosis. This case demonstrates the ability of rest/stress PET to identify not only CAD, but the severity. The accuracy of PET to predict multivessel CAD is significantly better than SPECT (Courtesy of Gary V Heller, MD, PhD).

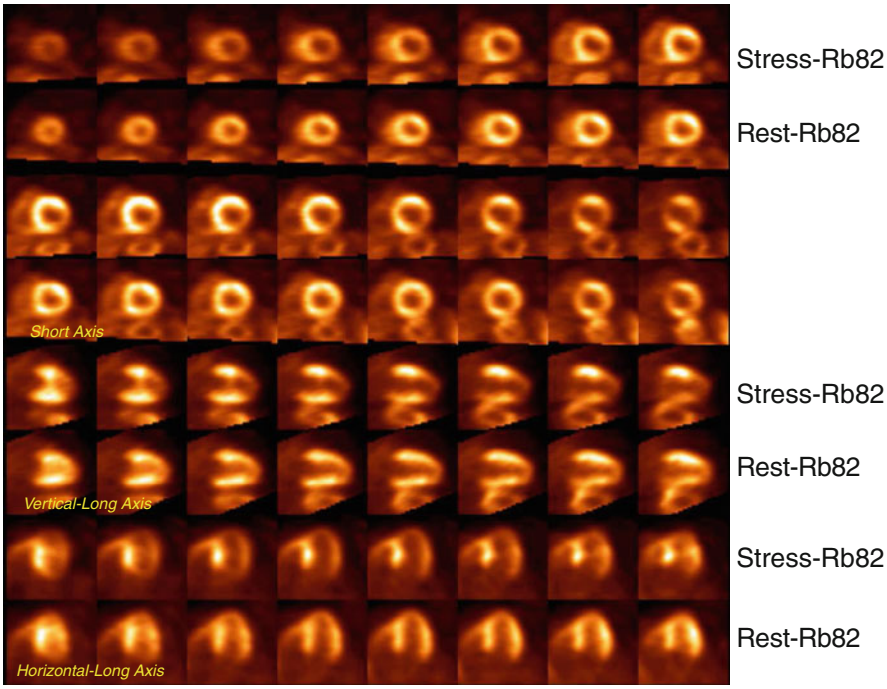

Fig. 9.4 Case #1 (see text for details)

Case 2

Sixty-eight year old female patient presents with congestive heart failure and chest pain. The patient's history includes hypertension, and prior MI several years previous. The patient had no history of diabetes. She had been stable until recent chest pain.

The patient underwent cardiac catheterization which demonstrated a 60% stenosis of the left anterior descending (LAD) artery and occluded obtuse marginal artery as well as an occluded right coronary artery with collateralization from the LAD. The patient under went a rest/stress dipyridamole PET protocol to evaluate for stress-induced ischemia and myocardial viability, in view of the diseased LAD and occluded vessels. The patient had no symptoms or ECG changes during the pharmacologic stress Fig. 9.5.

Illustrates the rest/stress Rb-82 results, with an FDG viability assessment. There was normal perfusion in the anterior region with severe fixed defects in the lateral and inferior regions. Gated PET imaging revealed akinesis of portions of the lateral wall as well as inferior, with LVEF at both rest and stress of 34%. The conclusion was that there was no stress-induced-ischemia and non-viability of the inferior and lateral regions consistent with the occluded vessels. Because the ischemia work-up did not demonstrate myocardial viability in areas of concern, a cardiac PET FDG

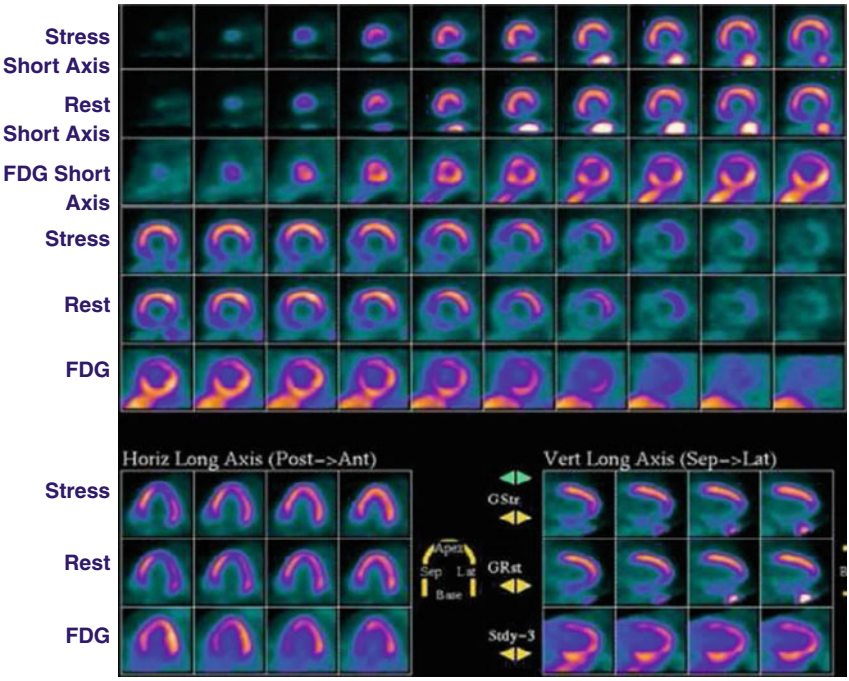

Fig. 9.5 Case #2 (see text for details)

study was performed, which demonstrated marked FDG activity in both the inferior and lateral walls as well as the anterior wall ("mismatch") consistent with myocardial metabolic viability in both the circumflex and right coronary arteries.

The patient underwent successful by-pass surgery with revascularization of all three major arteries. Six months later the patient was asymptomatic and an echocardiogram revealed mild/moderate hypokinesis of the lateral/inferior walls, with a global ejection fraction of 46 % (Courtesy of Gary V Heller, MD, PhD).

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Chapter 10
Radionuclide Angiography

Cesia Gallegos

Left ventricular function is a key measure for the assessment and management of cardiac conditions, especially in patients with heart failure and/or valvular disease. Noninvasive techniques can provide this information, as well as the assessment of regional wall motion abnormalities.

Radionuclide angiography (RNA) was first used in the 1970s, and is also known as radionuclide ventriculography (RVG), radionuclide cine angiography (RNCA), multiple gated cardiac blood pool imaging (MUGA) scan, and equilibrium radionuclide angiography (ERNA) [1, 2]. This radioactive count-based technique provides an accurate and highly reproducible method that is independent of ventricular geometry and is well suited for the serial assessment of global left ventricular (LV) function. This method may also be used in conjunction with bicycle exercise, although this is now infrequently performed. Parameters obtained from RNA include the following: global ventricular systolic function, regional wall motion, ventricular volumes, systolic and diastolic function indices, and stroke volume/cardiac output [2].

Indications

1. Evaluation of cardiac function in patients receiving chemotherapy: Perhaps the common indication, especially in evaluating for chemotherapy-induced cardiotoxicity, such as with doxorubicin, which may cause a dose-dependent impairment of the LV function, producing a severe and irreversible ventricular dysfunction before the onset of symptoms of heart failure. In this setting, RNA is a tool that provides quantitative measures of LV dysfunction in patients who

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are or have received therapy with doxorubicin. It can be used for risk stratification or prognosis, providing information on patients with preexisting cardiac conditions who are at greater risk of developing heart failure. Furthermore, serial evaluation of the LVEF (left ventricular ejection fraction) at rest can be performed on patient during follow-up while on these therapies, providing essential details to decide when doxorubicin will be stopped.
2. Known or suspected myocardial infarction
3. Known or suspected coronary artery disease (CAD)
4. Patient with heart valve disease
5. Evaluation of heart failure
6. Other applications: RV dysplasia, cardiomyopathies, aortic regurgitation, candidates for cardiac resynchronization therapy (CRT), candidates for lung transplantation, and candidates/monitoring of heart transplantation.

Contraindications

1. Pregnancy
2. Breast-feeding, depending on the technique used for labeling red blood cells (RBCs). For instance, for in vivo labeling, it is recommended to stop breastfeeding for at least 12–24 h after the injection.
3. Patients with cardiac arrhythmias, as interpretation may be limited by an irregular heartbeat. Although with "list mode acquisition" the RR variability can be corrected, the results may still be unreliable.

Equipment

RNA is performed by labeling a patient's red blood cells with a radionuclide, technetium-99m-pertechnate (Tc99m) or human serum albumin (HSA). Therefore, standard IV supplies are required. The labeling of RBCs with Tc-99m is performed through the use of FDA approved kits for the in vitro preparation of the Tc-99m labeling. Its content is not administered to the patient. Each kit consists of three separate nonradioactive components: A 10 ml reaction vial with stannous chloride, dextrose and sodium citrate, a syringe with sodium hypochlorite that must be protected from light to prevent degradation of the solution and a second syringe with citric acid, sodium citrate, and dextrose. RBCs are prepared with the solutions in the kit and then the Tc-99m is added and once labeled, the RBC should be injected to the patient within 30 min.

Image acquisition requires a standard gamma camera equipped with appropriate collimation. For first-pass RNA however, a dedicated gamma camera with a high counting efficiency is used for best results. Images will require a workstation for post-processing. In addition, EKG leads will be placed for monitoring and for gated image acquisition. Basic life support and resuscitative drugs must be available [2].

Technique

As is true for any diagnostic procedure, a complete history and physical examination must be performed, focusing on indications for testing, current medications, and allergies/side-effects, cardiac risk factors and current symptoms, as well as prior cardiac procedures, physical limitations and special precautions. An EKG must be obtained prior to the study to identify any heart rate variability as it may limit the ability to interpret the test. Additionally, Occupational Safety and Health Administration (OSHA) guidelines for handling of blood products and radioactive material must be followed [2].

For RBC labeling, it can be performed *in vivo*, modified *in vivo*, or *in vitro*, with the *in vitro* method being used most often [4]. The *in vitro* method is performed by drawing blood from the patient and then the stannous ions are injected to the blood with the subsequent addition of the Tc-99m to the mixture [4]. While in the *in vivo* method, two consecutive injections are required: the ions are injected directly to the patient's bloodstream, followed by the injection of the Tc-99m perctechnetate about 20–30 min later. The newly developed *in vivo* labeling technique, called modified *in vivo*, isolates the pretinned RBCs and Tc-99m from other body compartments during labeling. Tc-99m radiolabeled human albumin is an alternative, however the resulting images are of lower quality. The usual administered activity is 555–1110 MBq.

RNA can be performed as "first-pass" or as "equilibrium" [4]. The first-pass approach observes a bolus of Tc-99m perctechnetate or Tc-99m diethylenetriaminepentaacetic acid (DTPA) pass through the right side of the heart to the left and it can sample multiple cardiac cycles, determining the changes of radioactivity over time. This allows for the generation of time-activity curves to provide ejection fraction (EF) measurement of both the right and left ventricles, as well as accurate quantitation of regurgitant lesions. For the RV phase, two to five cycles are summed, and five to seven cycles are summed for the LV phase, from which LVEF and RVEF can be performed. This approach is also well suited for shunt detection and evaluation of RV function, but requires specialized cameras with high count rate capability and is infrequently performed.

With equilibrium RNA, Tc-99m pertechnate bound to RBCs is the most used [4]. The acquisition time range is 5–10 min per view, involving hundreds to thousands of heartbeats, which are synchronized with the QRS complex. Every cardiac cycle is divided into frames, and all the frames within a given RR interval. Equilibrium studies can be performed during rest or stress, and can be acquired by both planar and SPECT (single photon computer tomography) methods [3]. Equilibrium RNA uses the best septal left anterior oblique (LAO) projection, whereby the intraventricular septum is as vertical as possible. Lateral and anterior views are then obtained, each approximately 45° from the LAO projection (Fig. 10.1). For LVEF measurement, the LAO provides the best measurement since this projection separates the RV and LV and identifies anterolateral, posterolateral, and septal LV motion. Regional wall motion may also be assessed (Fig. 10.2). Quantification of volumes as well as systolic and diastolic function is derived from the ventricular time-activity curve [4].

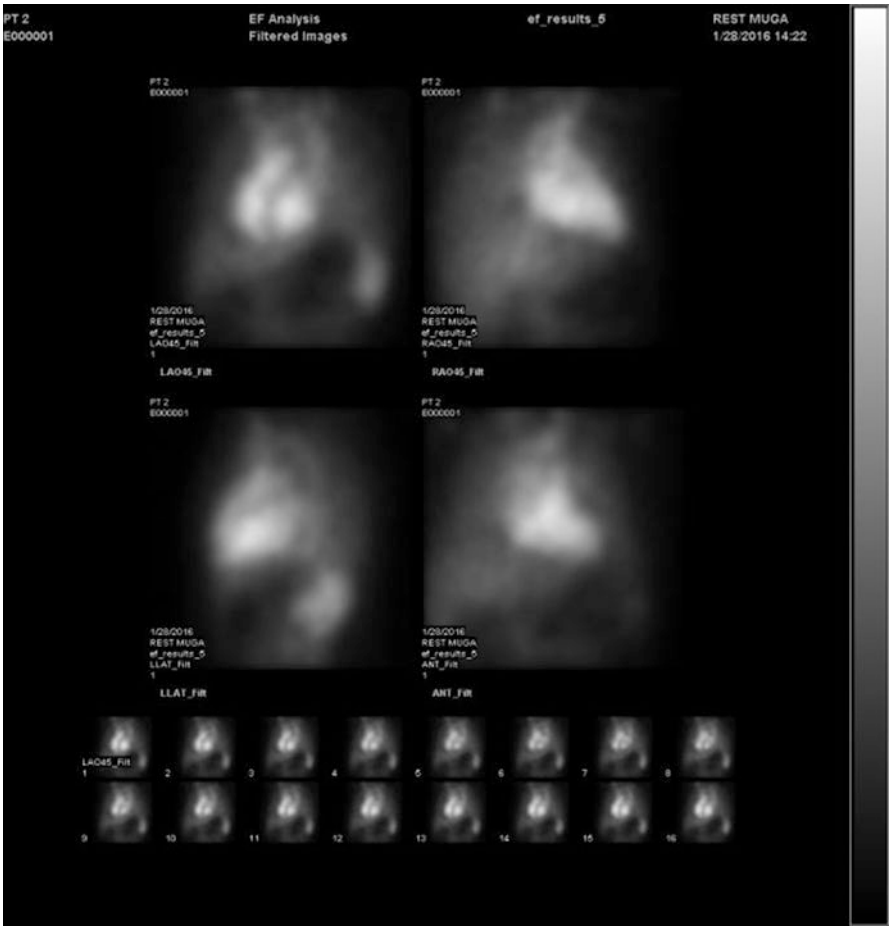

Fig. 10.1 Screen shot obtained at end-diastole demonstrating LAO (*upper left*), anterior (*upper right*) and lateral (*lower left*) planar projections. Regional wall motion is also displayed in the LAO image

Data Interpretation

The findings obtained from an RNA scan should be interpreted and reported in a systematic way. The essential components are: [2]

(a) Cardiac Morphology: Size, orientation, and morphology of various cardiac chambers, ventricular wall thickness, as well as the pericardial silhouette, which may all, be evaluated subjectively and reported. When measured, absolute volumes may be included.
(b) Systolic Ventricular function: All LV segments should be assessed qualitatively and global LV function should be compared to calculated

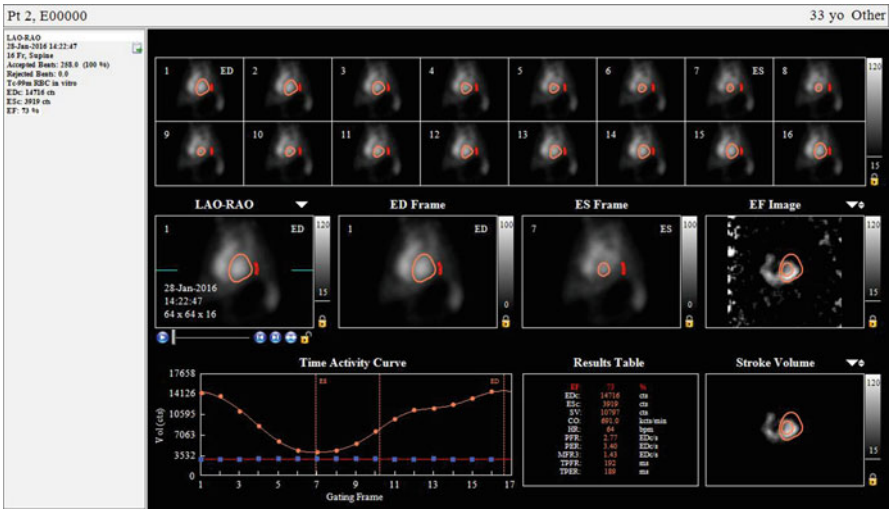

Fig. 10.2 Case 1 (see text for details)

EF. Reprocessing may be necessary, if there are discrepancies with measurements. Abnormalities should be reported as mild, moderate or severe, hypokinesia, dyskinesia, or akinesia. It is optional to report diastolic filling indices or systolic emptying indices.

(c) Stress images: These should be displayed side-by-side to the rest images in cinematic mode. Baseline, peak and recovery LVEF should be reported as well as any alteration in regional wall motion, RV and LV function and volumes. Cardiac morphology should be reported in a similar way as in a rest study.

(d) Comparison to other studies: Prior studies should be reviewed and compared

Additionally, diastolic function may also be assessed, especially with an acquisition greater than 16 frames per cardiac cycle, although this is infrequently performed at the current time. Indices such as peak filling rates and time to peak filling may be quantitatively determined.

Complications

RNA is a safe noninvasive procedure, however there are a few scenarios that require special caution.

1. Arrhythmias, in particular during or after stress/exercise as heart rate response during these is unpredictable
2. Incorrect handling of RBCs during in vitro, which may results in administration of the labeled cells to the wrong patient.

Clinical Vignettes

Case 1

A 43-year-old woman was recently diagnosed with breast cancer, treated with lumpectomy and radiation therapy. She is now scheduled to begin chemotherapy with a variety of agents, including doxorubicin. An RNA is performed to obtain a quantitative assessment of LV function.

Figure 10.2 demonstrates on a single static screen capture most of the key information needed to assess cardiac function and subsequently begin chemotherapy. This depicts a study with a 16 frame per cardiac cycle acquisition. The time activity curve at the bottom depicts LV filling during the cardiac cycle and even demonstrates the atrial contribution near the end of diastole. The ED and ES frames demonstrate the area of the LV during end-systole and end-diastole, with the adjacent region used for background counts. Our patient's quantitative LVEF was 73 %.

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Chapter 11
Cardiac Computed Tomography (CT)

Arieh Fox

Cardiac CT has undergone dramatic advances in technology with applications that include the assessment of coronary artery disease (CAD), using coronary computed tomography angiography (CCTA) evaluation of congenital abnormalities and structural function, and characterization of anatomy prior to valve and electrophysiology procedures [1, 2]. CT now permits the rapid acquisition of high quality data in the majority of patients using prospective (radiation-sparing) or retrospective ECG gating, with outstanding resolution of the coronary arteries as well as other cardiac structures.

Indications

In 2010, the ACCF/SCCT/ACR/AHA/ASE/ASNC/NASCI/SCAI/SCMR Appropriate Use Criteria for cardiac Computed Tomography was published with the level of appropriateness to guide physicians. The list is extensive and generally includes usefulness in the acute and chronic setting as well as in the symptomatic and asymptomatic patient. The main appropriate indications are listed below (Table 11.1).

Contraindications

Patients must be able to meet the weight requirements of the scanner, have the ability to lay supine and motionless with arms raised above their shoulders, and follow simple breathing instructions.

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Table 11.1 Appropriate indications for cardiac computed tomography [1, 2]

1	Detection of CAD in intermediate risk symptomatic patients without known heart disease
2	Detection of CAD in low risk symptomatic patients without known heart disease who are unable to exercise or ECG is uninterpretable
3	Detection of CAD in low & intermediate risk acutely symptomatic patients without known heart disease
4	Detection of CAD/risk assessment in asymptomatic low risk patients with significant family history or intermediate risk patients with coronary calcium score in individuals without known CAD
5	New-onset or newly diagnosed Heart Failure (HF) and no prior CAD in low & intermediate risk patients
6	Preoperative coronary assessment prior to non-coronary cardiac surgery in intermediate risk patients
7	Normal ECG exercise test & continued symptoms or Duke Treadmill Score-intermediate risk findings
8	Discordant ECG exercise and imaging results or equivocal stress imaging results
9	Evaluation of new or worsening symptoms in the setting of normal past stress imaging study
10	Evaluation of graft patency after CABG in a symptomatic patient
11	Assessment of anomalies of coronary arterial and other thoracic arteriovenous vessels or complex adult congenital heart disease
12	Evaluation of left ventricular function in acute Myocardial Infarction (MI) or HF when images from other noninvasive methods are inadequate
13	Quantitative evaluation of right ventricular function
14	Assessment of right ventricular morphology in suspected Arrhythmogenic Right Ventricular Dysplasia
15	Characterization of native and prosthetic cardiac valves with suspected significant valvular dysfunction and inadequate images from other noninvasive methods
16	Evaluation of cardiac mass (suspected tumor or thrombus) with inadequate images from other noninvasive methods
17	Evaluation of pericardial anatomy
18	Evaluation of pulmonary vein anatomy, coronary vein mapping or localization of coronary bypass grafts prior to intervention

Chronic Kidney disease (GFR <60) is a relative contraindication given the potential for contrast-induced nephropathy (CIN); the risk of CIN must be weighed against the potential benefits of the study. However, severe kidney disease (GFR <30, not on dialysis) is an absolute contraindication and an alternative testing strategy should be pursued. Previous anaphylaxis to iodinated contrast or an allergic reaction to iodinated contrast after premedication is an absolute contraindication.

Atrial fibrillation and frequent ectopy are relative contraindications to CCTA and mandate retrospective gating (acquisition of the entire cardiac cycle) if performed at all. Additionally, heart rates in excess of 70 BPM are usually associated with excessive cardiac motion and efforts to modulate pulse rate must be undertaken. In this regard, an inability to tolerate beta-blockers may be a relative contraindication.

In younger individuals, the risk of potential long-term radiation exposure must be weighed against the potential benefits of the study. Additionally, dense coronary calcification may limit the interpretation and utility of the study, however a specific coronary calcium (Agaston) score that excludes the use of CCTA has not been recommended in the Society of Cardiovascular Computed Tomography (SCCT) guidelines.

Equipment

Cardiac CT imaging equipment must meet the minimal technical capabilities required for the scan indication and the patient's underlying characteristics. According to the ACCF/SCCT/ACR/AHA/ASE/ASNC/NASCI/SCAI/SCMR Appropriate Use Criteria, cardiac CT generally requires a minimum of 64 multi-detector rows, gantry rotation time no greater than 420 ms, sub millimeter spatial resolution and cardiac imaging software capable of three-dimensional post processing with reconstructed axial data, multi-planar reconstructions, and maximum intensity projections. Additionally, tube potential adjustment must be available for radiation reduction techniques, such as reducing the voltage to 100 mV for non-obese patients. Ideally, prospectively triggered ECG scanning and iterative reconstruction should also be available for further radiation reduction.

Technique

Heart rate control is crucial for obtaining optimal images without significant artifact and therefore the patient should be given oral beta-blockers the night prior and the morning of the procedure. If the patient's heart rate is still elevated (>65 BPM), the patient should be given an additional dose of IV beta-blocker or calcium channel blocker as needed. Patients should abstain from caffeine or nicotine for at least 12 hours prior to procedure for purposes of heart rate control.

Nephrotoxic drugs should be discontinued and the patient should be screened for contrast induced nephropathy risk factors (diabetes mellitus, chronic kidney disease, congestive heart failure, age >75…) with an accurate history and a serum creatinine obtained prior to the procedure. Pre-procedural oral and possibly IV hydration may be necessary based on the patient's baseline serum creatinine. Patients with a history of an Iodine allergy or an allergic contrast reaction require premedication with corticosteroids and histamine antagonists.

Breath holds are performed during image acquisition and theoretically reduce cardiac motion as well as decrease intrathoracic pressure leading to maximum superior vena cava flow and contrast enhancement.

A coronary scan (CCTA) should begin at the level of the carina or mid-pulmonary artery and end 2 cm below the diaphragm unless the patient has bypass grafts, which would require starting above the arch. A calcium score is often obtained prior to coronary CT for prognosis and estimate of plaque burden, as well as to optimize CCTA image acquisition.

Nitroglycerin 0.4–0.8 mg sublingual should be administered prior to image acquisition to improve image quality by arterial vasodilatation. However, this should be avoided in patients with systolic blood pressures less than 100 mmHg, significant aortic stenosis or hypertrophic cardiomyopathy and patients who are using phosphodiesterase inhibitors.

The appropriate gating technique should be selected based on the study indication and the patient's characteristics. Prospective gating limits the data acquisition period during the cardiac cycle to the points of least coronary movement and is the preferred method for coronary artery assessment given its ability to obtain the necessary data while substantially limiting radiation exposure. Retrospective gating acquires data during the entire cardiac cycle and requires a significantly higher radiation exposure. This may be useful for patients with arrhythmia, rapid heart rates or high calcium scores, where artifacts may be a limiting factor and the additional data acquired throughout the cardiac cycle may be beneficial. ECG pulsed tube current modification is another gating technique used to limit radiation when coronary anatomy and evaluation of left ventricular function is required. Tube voltage and current should also be adjusted according to the patient's size to minimize radiation dose.

Contrast used in cardiac CT is nonionic with high iodine concentration typically dosed according to patient BMI and given through a vein suitable for administration at a flow rate of 4–6 mL/s (usually antecubital). Decreased and increased cardiac output increase and decrease the amount of contrast required.

Data Interpretation

The Society of Cardiovascular Computed Tomography (SCCT) released updated guidelines in 2014 on the interpretation of coronary CT angiography that are listed in the table below (Table 11.2).

Individual lesions should be graded on a qualitative and quantitative basis with the recommended SCCT scale listed below and plaque morphology should also be described as calcified, non-calcified or mixed (Table 11.3 and 11.4).

Additionally, myocardial chamber cavities and walls should be examined for dilation, hypertrophy, thinning, hypodense enhancement, shunting, masses and congenital anomalies. Reporting of left ventricular and regional function as well as valvular pathology may be appropriate depending on the clinical indication.

Reports should include a procedure section with complete details of image acquisition and image reconstruction and a clinical findings section with coronary findings, non-coronary cardiac findings, and non-cardiac findings.

Table 11.2 SCCT interpretation guidelines [3]

Non-contrast coronary calcium CT	
1.	Agatston score should be calculated for the total study (sum of 4 vessels)
2.	Presence of calcium in aortic wall, aortic valve, mitral annulus/valve, pericardium, and myocardium should be documented
3.	Noncardiac structures (pleural effusions, pulmonary nodules, mediastinal abnormalities, and so forth) should be documented
Coronary CT	
1.	Interpretation should be made on 3-dimensional cardiac-specific interpretation software
2.	Recommended image reconstructions should be viewed
3.	Interpreters should be prepared to customize image reconstructions if necessary
4.	The data set should be previewed for artifacts
5.	Noncontrast studies should be reviewed before contrast studies
6.	The coronary tree should be examined systematically
7.	Lesions should be reviewed in multiple planes and conceptualized in 3 dimensions
8.	Lesions should be assessed for stenosis severity, quality, and morphology of plaque
9.	Extracoronary cardiac and thoracic anatomy should be examined within the cardiac field of view

Table 11.3 SCCT recommended qualitative stenosis grading [3]

0	Normal	Absence of plaque and no luminal stenosis
1	Minimal	Plaque with negligible impact on lumen
2	Mild	Plaque with no flow-limiting stenosis
3	Moderate	Plaque with possible flow-limiting disease
4	Severe	Plaque with probable flow-limiting disease
5	Occluded	

Table 11.4 SCCT recommended quantitative stenosis grading [3]

0	Normal	Absence of plaque and no luminal stenosis
1	Minimal	Plaque with <25 % stenosis
2	Mild	25–49 % stenosis
3	Moderate	50–69 % stenosis
4	Severe	70–99 % stenosis
5	Occluded	

Complications

Potential complications from cardiac CT include iodinated contrast extravasation, which can rarely lead to ulceration or compartment syndrome, allergic reactions to iodinated contrast, contrast induced nephropathy and radiation exposure. CIN is generally defined as a change in serum creatinine of >0.5 mg/dL or a >25 % increase in serum creatinine from baseline within 2–3 days of contrast exposure. Risk factors for CIN include hypotension, congestive heart failure, chronic kidney disease, diabetes, age older than 75, anemia, and volume of contrast. Radiation exposure should always be limited to as low as reasonably achievable while still obtaining the necessary results for an appropriate study.

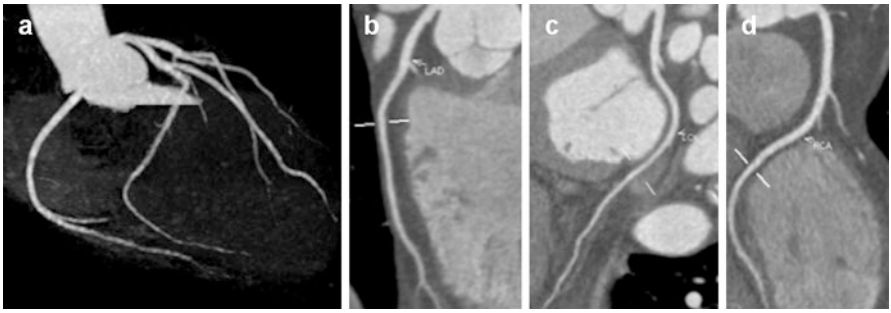

Fig. 11.1 Case #1 (see text for details)

Clinical Vignettes

Case 1

Forty-five-year-old police officer, who is active at baseline and has no significant past medical history presents to the emergency department (ED) after experiencing an episode of sharp chest pain earlier in the day. In the ED, the patient was noted to have an ECG without significant abnormalities and an elevated blood pressure of 160/105 mmHg. CCTA was obtained for detection of CAD in this low risk acutely symptomatic patient (Fig. 11.1).

This case shows a CCTA with no significant atherosclerotic lesions of the coronary arteries. Included below are the curved multiplanar reformation images of the Left Anterior Descending (LAD) artery (Fig. 11.1b), Left Circumflex (LCx) artery (Fig. 11.1c) and the Right Coronary (RCA) artery (Fig. 11.1d) without evidence of significant atherosclerotic disease.

Case 2

Sixty-four-year-old man with a past medical history significant for hyperlipidemia presents requesting a preventive cardiovascular evaluation. Previously, the patient underwent an asymptomatic treadmill stress test with 3 mm ST depressions in the inferolateral leads followed by a nuclear stress test with abnormal ECG findings but normal scintigraphic images without evidence of ischemia. Given discordant ECG exercise and imaging results, a CCTA was obtained for further evaluation.

This case shows a CCTA with severe coronary calcification and significant CAD in two vessels. There is extensive calcification in the proximal portion of the LAD with an elongated non-calcified severely stenotic plaque of approximately 70–99 % (Fig. 11.2b). There is also calcification noted in the LCx but without significant obstruction (Fig. 11.2a). The proximal portion of the right coronary artery contains

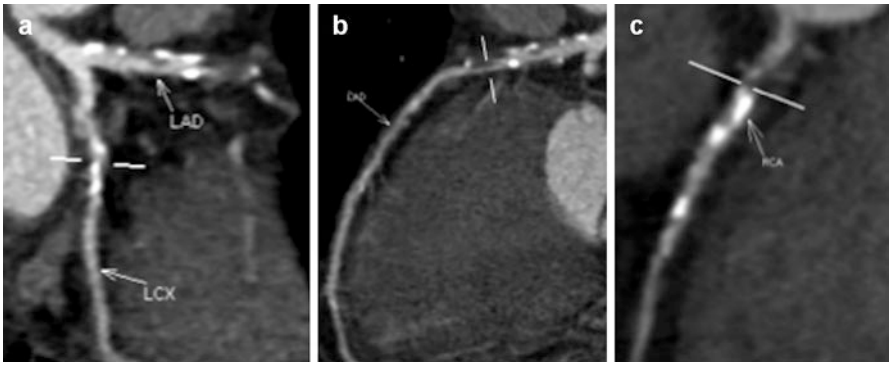

Fig. 11.2 Case #2 (see text for details)

extensive calcification and an area of low density with markedly reduced contrast, which suggests a severe stenosis of 70–99 % (Fig. 11.2c).

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Chapter 12
Cardiac Magnetic Resonance

Cesia Gallegos

Cardiac magnetic resonance (CMR) is an imaging modality used for the assessment of heart, providing both anatomic and physiologic information. Its use has increased over the last decade given the improvement on imaging acquisition and quality with growing evidence from clinical trials supporting its value. The high natural contrast between intracardiac or intravascular blood pool, lack of ionizing radiation, and three-dimensional nature of this method provide substantial advantages over other methods, but it is the ability of CMR to characterize tissues that offers unique value of this technique.

Indications (Table 12.1)

Cardiac anatomy and ventricular function CMR is considered the most reproducible and accurate in the study of left ventricular (LV) function. Some of the parameters routinely reported in functional CMR may include: LV end-diastolic volume (LVEDV) and LVEDV index, LV stroke volume, LV ejection fraction (LVEF), LV mass index, and LV end-diastolic and end-systolic diameter. CMR may also be used for qualitative and quantitative assessment of global and regional wall motion of the right ventricle (RV). It is usually the first-line diagnostic test for assessing RV function and it is indicated in the evaluation of patients for suspected arrythmogenic RV cardiomyopathy or dysplasia, as well as pulmonary arterial hypertension.

Congenital heart disease CMR may be used for the assessment of congenital shunts, specifically to quantify and follow right and left ventricle volumes and func-

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Table 12.1 Class I and II indications for CMR [1–4]

Indication	Class
Arrythmogenic right ventricular dysplasia	I
Siderotic cardiomyopathy (in particular thalassemia)	I
Dilated cardiomyopathy	I
Hypertrophic cardiomyopathy (apical)	I
Non compaction cardiomyopathy	II
Ventricular thrombus	II
Constrictive pericarditis	II
Restrictive cardiomyopathy	II

tion. CMR is also useful in some forms of atrial (ASD) or ventriculoseptal (VSD) defects that are challenging for other imaging modalities to identify. The use of CMR along with angiography and flow measurement is also valuable for the assessment of complex congenital anomalies and the determination of chamber size, function, and atrial-ventricular relationships. Other congenital conditions in which CMR has proven to be helpful include pericardial anomalies, as well as valve disease and coronary artery anomalies.

Assessment of the great vessels It can frequently demonstrate a lesion directly (stenosis) or indirectly, by showing a signal loss resulting from phase incoherence (abnormal communication). CMR angiography is also used to depict the extent, size, and shape of aortic aneurysms dissections, thrombus, vascular wall, and adjacent soft tissues. Its lack of ionizing radiation provides a tool for serial imaging.

Acquired myocardial and pericardial disease One of the most valuable uses of CMR is the assessment of adult cardiomyopathies, myocardial fibrosis and infarction, as well as pericardial disease, including collections, masses, and effusions. Through the use of phase contrast techniques, CMR can also evaluate for valvular stenosis or insufficiency. It also characterizes specific tissue configurations of tumors and masses and their relationship to chambers and valves, making it the ideal imaging modality as it allows for the assessment of mediastinal, pericardial and myocardial involvement in one single study.

Coronary artery disease CMR is also useful in the evaluation of chronic ischemic heart disease, especially with the delineation of myocardial viability through the use of gadolinium. Vasodilator stress perfusion imaging and dobutamine wall motion assessment are CMR techniques for the detection and quantitation of inducible ischemia.

Contraindications

CMR is safe and lacks ionizing radiation, but special caution should still apply. In all cases, a risk/benefit consideration should be performed prior to each test and must be informed to each patient. This involves a physician with thorough

knowledge of patient safety, possible neurological effects, tissue heat deposition, the use of contrast as well as other contraindications or special considerations, which include [3]:

Implantable Devices Common implants, which may present a hazard when undergoing CMR, include pacemakers, ICD's, cochlear implants, neurostimulators, hydrocephalus shunts, metal-containing ocular implants, pacing wires, and metallic cerebral clips [5]. A full list is available in www.mrisafety.com. The clinician must be aware if the patient has an implantable device and whether or not it is magnetic resonance (MR) safe, conditional or not safe. If decision is made to perform CMR to a patient with a device, knowledge of device programming is necessary. Some of the risks of performing CMR in patients with pacemaker or cardioverter-defibrillators include burns from generation of an electrical current from the metallic hardware and the "antenna effect", device movement, inappropriate discharging and sensing. Appropriate emergency equipment and medications to treat possible adverse reactions must be readily available.

Contrast media Although more frequent with the use of iodinated contrast, some patients may require pretreatment prior to injection of contrast media even if gadolinium is used for prevention of anaphylactic reaction and/or acute kidney injury. Special caution must be performed in patients with decreased renal function, especially with a GFR <30 mL/min due to the risk for nephrogenic systemic fibrosis, a potentially catastrophic complication of gadolinium exposure.

Pharmacological stress testing in unstable patients similar to any other stress test modality.

Equipment

The magnetic resonance imaging (MRI) equipment must meet all state and federal requirements and must be accredited by the Academic College of Radiology (ACR) [2].

MRI scanners for CMR must have the following specifications:

1. Field strength ≥1.0 T. Most common is 1.5 T
2. Slew rate of at least 70 mT/m/s.
3. MRI scanners should be equipped with ECG gating and multi-channel radiofrequency surface coil.
4. MRI-compatible power injector for myocardial perfusion CMR
5. Capability of fast 3D gradient echo imaging, phase-contrast flow quantification, and fast multislice myocardial perfusion imaging as well as delayed contrast-enhanced myocardial imaging.
6. FDA-approved software for processing data

Technique

MRI is based on imaging of protons within the hydrogen atoms in the human body that act as tiny magnets. A patient is then placed inside a scanner with a magnetic field, which the resultant vectors are fine-tuned by computer-controlled adjustments of small coils placed within the magnet [5].

Unless impeded by body habitus, a phased array surface coil should be used, as the heart is small and the visual field should be reduced to maintain adequate spatial resolution. CMR imaging techniques may vary depending on the indication. Nonetheless, most examinations include short and long-axis cine images from the heart obtained for ventricular function [3]. For assessment of cardiac morphology, T1-weighted and/or T2 weighted images of the heart may be beneficial and they should be gated to the R wave of the ECG.

For evaluation of mass, tumors, or cysts, pericardial disease, and myocardial inflammation, or perfusion, IV gadolinium is administered. Additionally, in the particular case of myocardial perfusion assessment, gadolinium must be rapidly bolused.

For flow quantification, phase contrast imaging may be used. CMR angiography can be used in addition to other MRI methods as it may provide important information about the great vessels.

CMR tagging is another technique in which bands are applied to the heart in end-diastole, and subsequently cine images are obtained to observe the movement of the bands, which may provide information about wall motion abnormalities.

Data Interpretation

The CMR imaging planes are oblique to one another and are called "double-obliques" planes as they are at arbitrary angles with respect to the scanner. There are three main planes in which the images will be reported: short axis, horizontal long axis or 4-chamber view, and vertical long axis or 2-chamber view.

Cardiac function is evaluated using cine gradient echo sequences called "bright blood sequences" used in conjunction with segmented k-space acquisition. For evaluation of cardiac morphology "black blood "sequences are also used, for which there are multiple options: half-Fourier, single-shot, fast spin echo (SS-FSE) being the most common. Ventricular function can then by quantitatively assessed by reviewing the dynamic images. For example, chronic transmural ischemia will be demonstrated by a decrease in the myocardial thickness to less than 6 mm and will also exhibit a lack of wall thickening during systole. Additionally, myocardial tagging is used to track segmental motion and helps to distinguish compromised myocardium from myocardium that may move irregularly because of its proximity to an affected area. However, a more reliable indicator of acute myocardial infarction is delayed contrast enhancement after the administration of IV gadolinium, which

demonstrates a good correlation between healthy and infarcted myocardium. In infarcted cells, the gadolinium is retained after a period of washout of other regions (about 5–10 min), resulting in delayed hyperenhancement. This is particular useful as a greater extent of transmural infarction can predict areas that are unlikely to improve after revascularization.

Complications

1. Ferromagnetic items can possibly be dangerous projectiles in the scanner room and can injury patients and staff
2. Heating of wires of pacemakers and defibrillators, which could result in serious burns.
3. Nephrogenic sclerosing fibrosis in patients administered gadolinium that have a reduced GFR.
4. Claustrophobia

Clinical Vignette

Case 1

Sixty-seven year-old male with history of hypertension, diabetes type 2, and chronic obstructive pulmonary disease presented to the hospital with exertional chest pain, cough, hypoxemia and elevated troponins. As part of his evaluation, underwent cardiac catheterization which was non-revealing, and a 2D echocardiogram demonstrated a normal EF without wall motion abnormalities. Given nondiagnostic work-up, CMR was performed, shown in Fig. 12.1.

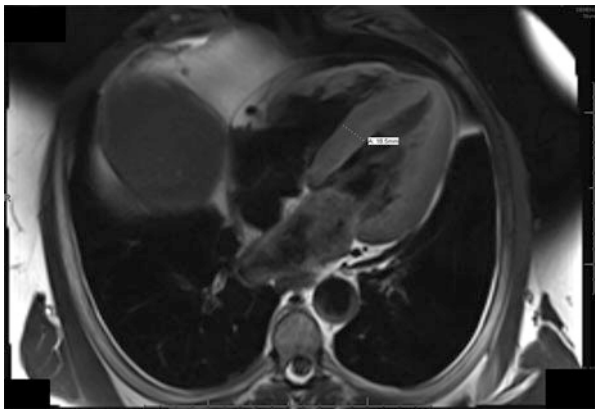

Fig. 12.1 Case #1 (see text for details)

The image shown demonstrates an end-diastolic myocardium measuring 18.5 mm at the septum, which was not previously seen on echocardiography. Patient was found to have COPD exacerbation and elevation of troponins was likely secondary to demand ischemia in the setting of hypertrophic cardiomyopathy, as they normalized once the infection was controlled. In this case, CMR allowed for the identification of LV hypertrophy in segments not visualized well with other diagnostic modalities.

Case 2

Fifty-three year old man presented following a 45 min episode of chest pain. His ECG revealed deep T wave inversions in the anterior leads but he was pain free. Echocardiography revealed anterior akinesis and an LVEF of 27 %. He was referred for CMR with LGE to assess myocardial viability.

Figure 12.2 demonstrates a large area of LGE in the anterior wall but it is subendocardial, not transmural. Base on this study, with the impression that substantial viability was present, he was referred for cardiac catheterization and underwent PCI of a proximal LAD lesion (90 %). Subsequently, an echocardiogram revealed marked improvement in anterior wall motion and an LVEF of 45 %.

Case 3

A 31 year old woman presented to her physician's office with severe shortness of breath. She had had an upper respiratory infection approximately 10 days ago, with rhinorrhea and cough, but her symptoms had almost completely resolved until 1 day

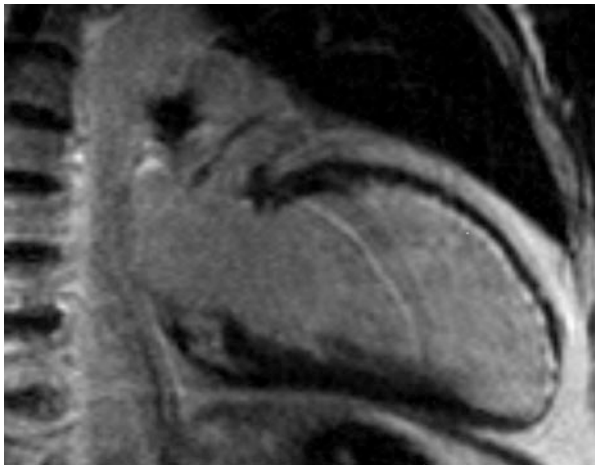

Fig. 12.2 Case #2 (see text for details)

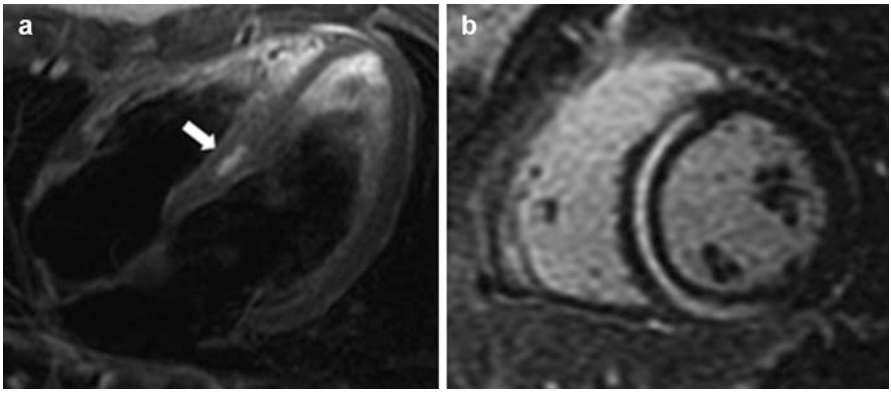

Fig. 12.3 Use of Cardiac Magnetic Resonance in the diagnosis of acute myocarditis. (**a**) Midseptal wall edema on T2 weighted images (*arrow*) (**b**) Prominent late gadolinium enhancement in the mid wall of the intraventricular septum

before presentation. She has no pre-existing medical conditions. A chest x-ray was compatible with pulmonary edema and an echocardiogram revealed severe left ventricular dysfunction. CMR was performed (Fig. 12.3).

These images depict midseptal wall edema on the T2 weighted images (Panel A) and prominent late gadolinium enhancement in the mid wall of the intraventricular septum (Panel B). These findings are consistent with acute myocarditis. After an initially labile hospital course, the patient demonstrated marked clinical improvement over the next week but did have some residual LV dysfunction on discharge.

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Part II
Critical Care

Chapter 13
Central Venous Cannulation

Saleh Alshalash and Carey Kimmelstiel

Introduction

Central venous cannulation is an essential skill for all cardiovascular specialists and provides a safe and secure route for the administration of parenteral agents. Often performed in an emergent fashion, when intravenous access is required for delivery of potentially life saving medications, this technique may also be used when limited peripheral options are available.

Indications

Central venous cannulation is required in a variety of clinical scenarios. Current critical care units utilize central venous lines for inotropic and vasopressor medications that require infusion via a central venous catheter. In addition, central access allows for insertion of multi-lumen catheters that can accommodate the infusion of non-compatible medications using a single access point. While peripheral intravenous lines remain the preferred method for large volume resuscitation, central lines are commonly used for this purpose. Hyperalimentation, temporary pacemaker implantation, right heart catheterization for invasive hemodynamic monitoring and right ventricular (RV) biopsy also require central venous access (Table 13.1).

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Table 13.1 Indications for central venous cannulation

Indications	
Infusion of vasoactive medications	Inadequate peripheral access
Right heart catheterization	Administration of medication known to cause phlebitis
Placement of pacing leads	Plasmapheresis
Monitoring of central venous pressure	Hemodialysis
Right ventricular biopsy	
Relative contraindications	
Bleeding diathesis	Active infection at the access site
Deep vein thrombosis	Known distorted anatomy (due to radiation or prior surgery)
Contralateral pneumothorax (for IJ and SC central lines)	High pressure ventilation

Contraindications

Bleeding is a relative contraindication and benefits should be weighed against risks. Active infection and deep venous thrombosis (DVT) at the site of cannulation are contraindications and if present, a different site should be used. For internal jugular (IJ) and subclavian (SC) venous access, contralateral pneumothorax or high pressure ventilator settings should prompt consideration of an alternative site (Table 13.1).

Equipment

Central venous cannulation requires a sterile field. Methodological full-body draping reduces the incidence of central venous line infections. Local anesthetic, an ultrasound machine with a sterile cover, central line access kit (which includes an 18-gauge needle, syringes, guide wire, scalpel, dilator, and central line -single or multi-lumen), sterile saline flushes, suture, and a dressing are needed to complete the procedure. The usual length of central venous catheters is 12–20 cm.

Technique

The site of access should be chosen carefully. The IJ, SC, and femoral veins are among the most widely accessed sites. Peripherally inserted central catheters (PICC) are also an option, particularly when the catheter is needed for a longer period of time (>1 week). Inspection of the site and using ultrasound to identify the target vessel prior to setting up a sterile field increases the odds of a successful procedure and obviates the need to change the site because of anatomical anomalies or DVT. Once the site is identified, meticulous antiseptic technique must be followed while preparing a sterile field and the access site. The use of ultrasound has become the standard of care in accessing the IJ vein as it has been shown to reduce the

incidence of carotid puncture, neck hematoma, hemothorax, pneumothorax, number of attempts, access time, and catheter related blood stream infection [1]. The vein is identified using ultrasound; it is compressible and has continuous flow compared to the pulsatile and not-easily compressible artery (Fig. 13.1).

Solely using anatomic landmarks to achieve IJ access, is discouraged as it is associated with a higher rate of complications [2]. The patient is placed in a supine or Trendelenburg position, the apex of the triangle formed by the two heads of the sternocleidomastoid and the clavicle is infiltrated with local anesthetic with the needle directed towards the ipsilateral nipple (Fig. 13.2). The use of a 22-gauge "finder" needle to cannulate the vein is sometimes performed to "map the way" for the 18-gauge needle.

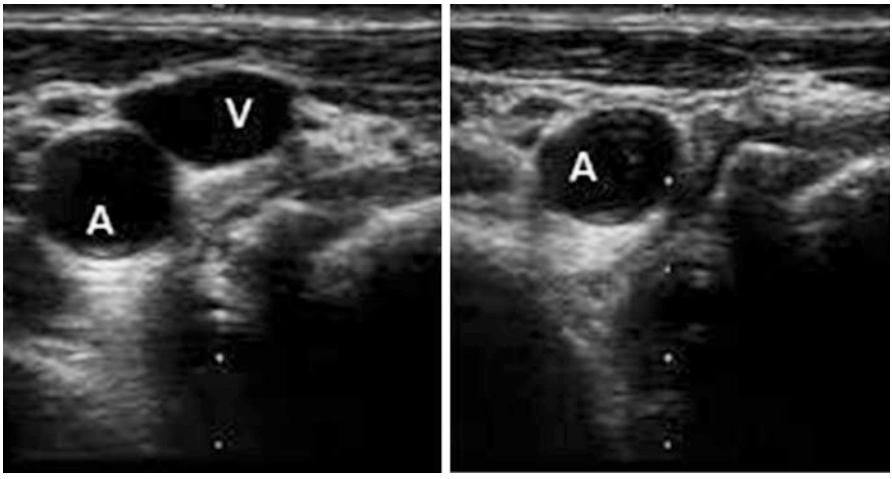

Fig. 13.1 The carotid artery (A) and the right internal jugular vein (V) are seen (*left image*) and after compression, the vein is no longer visible (*right image*)

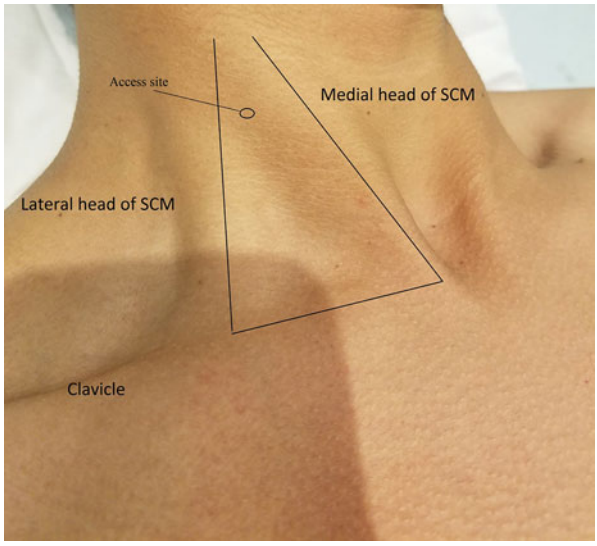

Fig. 13.2 Surface anatomy and landmarks for right IJ access. The apex of the triangle formed by the two heads of the SCM and the clavicle is accessed with the needle pointing towards the ipsilateral nipple (*SCM* sternocleidomastoid muscle)

For SC vein access, the needle is inserted at the point where the medial third of the clavicle meets the middle third (just medial to the midclavicular line) and the needle is inserted using a shallow angle underneath the clavicle with the needle pointing towards the suprasternal notch. The vein is cannulated underneath the clavicle. It is important to position the patient in a Trendelenburg position to distend the SC vein and increase the odds of venous cannulation. Some operators prefer placing a pillow or rolled-up towel under the patient, between their shoulder blades. In patients with coagulopathy the SC vein should, in general, not be used as it is non-compressible. Aspiration of bright red pulsatile blood indicates arterial puncture and the needle should be withdrawn and pressure is applied. Aspiration of air bubbles may indicate a pneumothorax. The SC vein is associated with less risk of catheter related systemic infection compared to femoral and IJ routes, but a higher risk of pneumothorax [3].

The femoral vein is accessed 1 cm below the inguinal ligament approximately 1 cm medial to the femoral artery. Central venous cannulation using the femoral vein can be done rapidly in unstable patients or during CPR, however, it may be associated with higher rates of catheter-related blood stream infections.

Once the vein being utilized is accessed with the 18-gauge needle, the guide wire is inserted and the dilator is passed over the wire to expand the puncture site to accommodate the catheter. The catheter is inserted over the wire, then aspirated, flushed, and sutured into place. When the IJ or SC veins are used, the tip of the catheter should be in the superior vena cava which is confirmed by a subsequent chest x-ray.

Data Interpretation

The size of the IJ vein when visualized with ultrasound and the respirophasic variation reflects the volume status of the patient as it is commonly a reflection of central venous pressure, except in situations where there is an obstruction caused by DVT, stenosis, or in the presence of moderate to severe tricuspid regurgitation. Once the vein is cannulated and the sheath is introduced, the central venous pressure can be directly measured using a standard fluid-filled transducer. If the operator is uncertain as to whether the vein or artery was cannulated, verification should be made prior to introducing a dilator into the vessel. There are many ways to verify that the vein was cannulated. A widely used method is observing the blood return, which is dark and has continuous flow in the central veins compared to bright red and pulsatile flow in the artery. When uncertainty exists, an oxygen saturation can be performed with a point of care device to assess whether the needle resides within the venous or arterial system. If an oxygen saturation is not immediately available, fluoroscopy can be utilized, following the course of the guidewire, with skilled operators able to discern the typical course of venous or arterial anatomy. An alternative method involves the infusion of a small amount of contrast which can discriminate between the pulsatile artery from the non-pulsatile

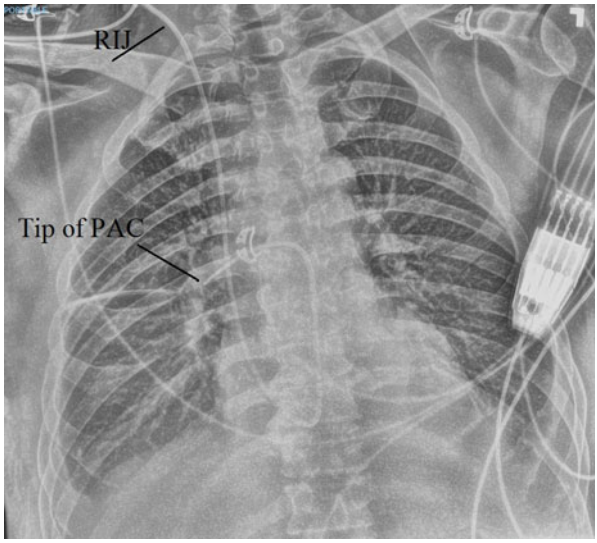

Fig. 13.3 Chest x-ray showing a pulmonary artery catheter (*PAC*) after insertion from the right IJ (*RIJ*) into the right pulmonary artery

vein. In the absence of fluoroscopy, the wire can be visualized in the long and short axes using ultrasound. If the operator is still uncertain that the needle is in a central vein, injection of small amount of agitated saline visualizing the trajectory of the fluid flow will help to confirm the position of the needle. Alternatively, a phased array probe can be used to visualize the agitated saline within the right sided cardiac chambers.

After central venous catheter placement, in the IJ or SC vein, an upright chest x-ray should be obtained to confirm the position of the central line and to exclude the presence of pneumothorax or hemothorax. Figure 13.3 depicts the course and position of a pulmonary artery (PA) catheter. Venous anomalies, such as persistent left superior vena cava (PLSVC) that drains into the coronary sinus, may present a confusing radiographic image when left sided venous access is used (Fig. 13.4) [4]. For central lines the chest x-ray is also helpful in confirming the distal tip of the catheter which should be above the cavoatrial junction to avoid precipitating atrial arrhythmias and possible trauma to the right atrium (RA) (Fig. 13.5). The correct position of the tip of the catheter should be in the superior vena cava (SVC) just proximal to the right atrium RA-SVC junction (Figs. 13.5 and 13.6).

Complications

Arterial cannulation, venous dissection, hematoma, catheter associated DVT or infection, pneumothorax, hemothorax, and atrial or ventricular arrhythmias especially during wire insertion are among the most common complications. Constant visualization of the needle tip, confirmation of the needle position after vessel

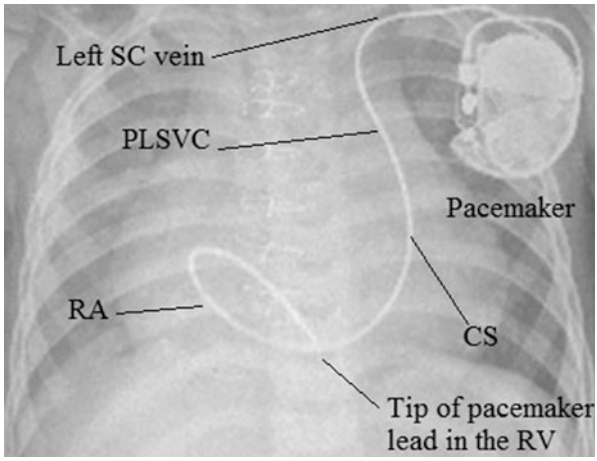

Fig. 13.4 Chest x-ray showing a left sided pacemaker that was implanted in a child with persistent left superior vena cava (*PLSVC*) draining into the coronary sinus (*CS*). The course of the venous drainage is delineated by the pacemaker lead (left SC vein which joins left IJ vein and become left SVC that drains into the coronary sinus which drains into the RA)

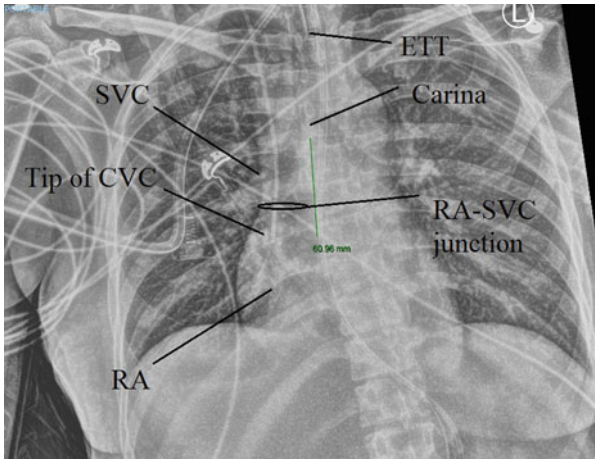

Fig. 13.5 Chest x-ray showing a central venous catheter (*CVC*) inserted into the right IJ passing through the superior vena cava (*SVC*) into the right atrium (*RA*). The tip of the CVC is seen approximately 1 cm below the RA-SVC junction

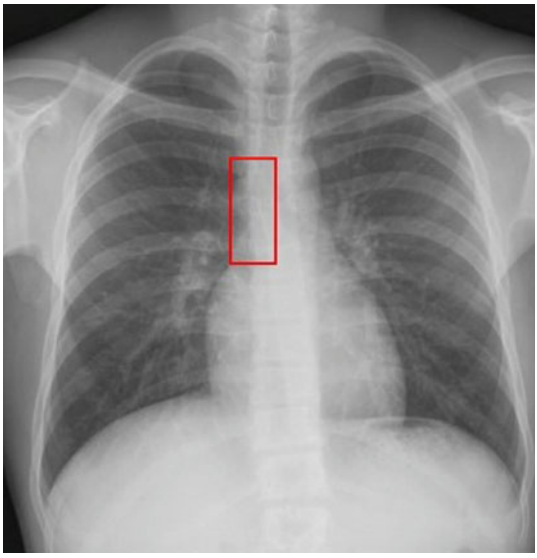

Fig. 13.6 Upright chest x-ray showing the desired position where the tip of the central line can be positioned (*rectangle*). Lower positions risk the possibility of atrial arrhythmias

cannulation, and meticulous sterile technique will aid in minimizing complications. Operators should be mindful of the distance between the skin and the anterior wall of the vein and expect blood return after the needle traverses that distance. If blood return is not seen, the operator should pause and identify the needle tip as it is not uncommon for the needle to compress the vein and travel through the posterior wall without blood return. In this instance, slow withdrawal of the needle should result in venous cannulation. Of note, access of left IJ or left SC vein carries a risk of chylothorax.

Clinical Vignettes

Case 1

A 50-year old male with history of DVT and pulmonary embolism, moderate tricuspid regurgitation, pulmonary hypertension, diabetes, hypertension and ischemic cardiomyopathy, presented with dyspnea, a productive cough, leukocytosis, and bilateral infiltrates on chest x-ray. Physical examination reveals heart rate of 115 beats per minute, regular pulse and a blood pressure of 85/50 mmHg. Auscultation of the chest reveals bilateral rhonchi, soft S1, normal S2, and an S4. Extremities are cool and bilateral lower limb swelling is noted. Right heart catheterization is planned to assess filling pressures, calculate cardiac output, and provide central venous access to infuse vasoactive medications.

In situations where the filling pressures are likely to help clinicians resuscitate patients with sepsis and heart failure, the insertion of a pulmonary artery (PA) catheter may be of value. The right IJ provides a direct access point for PA catheter insertion. This can be achieved with a 5–7 French sheath that can accommodate the PA catheter. Once the PA catheter is positioned correctly, vasoactive medications can be given via the lumens of the catheter.

Case 2

A 30-year old male with acute myeloid leukemia presented with fever and fatigue. Physical examination documented a heart rate of 125 beats per minute, BP 90/60 mmHg, with labs revealing pancytopenia with a profound reduction in the absolute neutrophil and platelet counts and an INR of 1.8. A central line was required for infusion of antibiotics and vasoactive medications and for measurement of CVP.

The risk of bleeding is considerable, therefore, the SC vein should be avoided. Correction of coagulopathy with platelet transfusion prior to the procedure, if feasible, may reduce the risk of bleeding.

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Chapter 14
Right Heart Catheterization

Christopher Madias and Carey Kimmelstiel

Introduction

In the catheterization laboratory and the intensive care unit, right heart catheterization (RHC) can provide vital physiologic information. Although clinical trials have never demonstrated improved outcomes with RHC, when used appropriately, it is viewed as an invaluable tool for the hemodynamic monitoring and management of critically ill patients with cardiovascular disease.

Indications

Situations in which RHC may be beneficial include evaluating the etiology of impaired oxygenation that remains uncertain (i.e., cardiogenic versus non-cardiogenic). Acute respiratory distress syndrome may be suggested as a cause of pulmonary edema in the presence of a normal or mildly elevated pulmonary capillary wedge pressure (PCWP). RHC can help guide treatment in patients with severe left ventricular dysfunction who show clinical deterioration despite application of standard therapies (e.g., concomitant pulmonary congestion with hypotension or signs of hypoperfusion). Titration of inotropic or vasodilatory therapy based on RHC hemodynamic information is commonly referred to as

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"hemodynamic tailored therapy." Such tailored therapy is often performed in patients following cardiac surgery and is often beneficial in managing high-risk cardiac patients (e.g., critical aortic stenosis) who are undergoing non-cardiac procedures or operations. RHC may also be beneficial in differentiating the cause of profound hypotensive states, especially when accurate assessment of volume status is limited by coexisting conditions, such as morbid obesity. A low cardiac output (CO) with elevated PCWP and high systemic vascular resistance (SVR) can indicate cardiogenic shock. A high cardiac output with normal or low PCWP and decreased SVR can indicate septic shock. A low or normal cardiac output with low PCWP and normal or high SVR can indicate hypovolemic shock. Hypotension with equalization of intra-cardiac diastolic pressures can indicate cardiac tamponade. Distinctive hemodynamic findings of constrictive and restrictive physiology can also be revealed by RHC. Finally, RHC can also be useful in establishing the diagnosis of pulmonary hypertension and assessing the response to vasodilator therapy. Assessment of pulmonary hypertension with RHC is an important step in the evaluation of the heart transplant candidate. Patients undergoing evaluation for heart transplantation, who have substantial pulmonary hypertension that is not reversible with vasodilator therapy, are considered poor candidates for transplant as right ventricular failure can develop in the transplanted heart [1].

A consensus statement containing specific recommendations on the use of RHC in various cardiovascular disease states was published by the American College of Cardiology in 1998. Table 14.1 summarizes some of the commonly accepted indications [2].

Table 14.1 Indications for right heart catheterization

Differentiation of profound hypotensive states (e.g., cardiogenic shock vs. septic shock vs. hypovolemic shock)
Guidance of therapy in severe left ventricular dysfunction—"hemodynamic tailored therapy"
Assessment of constrictive and restrictive physiology
Cardiac tamponade
Assessment of impaired oxygenation — cardiogenic vs. non-cardiogenic pulmonary edema
Evaluation of pulmonary hypertension
Management of high-risk cardiac patients undergoing non-cardiac procedure or surgery
Assessment of intra-cardiac shunts
Management of complicated myocardial infarction (e.g., cardiogenic shock, mechanical complications)
Management of patients following cardiac surgery
Heart failure with reduced or preserved ejection fraction (diagnosis and management)
Assessment of candidacy for heart transplantation
Left ventricular assist device dysfunction
Acute pulmonary embolism
Assessment of volume status in renal or hepatic failure
Post operative monitoring after cardiac surgery

Contraindications

A mechanical prosthetic tricuspid or pulmonic valve are generally considered absolute contraindication for right hear catheterization. Relative contraindications for RHC include coagulopathy or thrombocytopenia (INR >1.7 or platelet count <50,000). The ability to temporary pace the patient with left bundle branch block should be available during RHC as flotation of the pulmonary artery (PA) catheter through the right ventricle can induce complete heart block in up to 3 % of these patients [3]. Patients with intra-cardiac devices, such as pacemakers or implantable cardiac defibrillators, should have RHC performed under fluoroscopy to avoid the catheter tip getting caught in or dislodging a device lead. The presence of severe tricuspid regurgitation, right ventricular dilatation, and pulmonary hypertension might also necessitate the use of fluoroscopic guidance.

Equipment

The Swan Ganz PA catheter is the most widely used catheter for RHC. The balloon tip allows the catheter to follow the flow of venous blood through the right side of the heart to the PA. The catheter has multiple lumens that are accessed by various ports, including a proximal port, a distal port, and a balloon inflation port. These ports allow for the measurement of pressures as well as the sampling of blood oxygen saturation along the right side of the heart and the PA (Fig. 14.1). A thermistor mounted to the distal tip of the catheter allows for temperature measurements [1].

Technique

RHC can be performed via the superior vena cava with percutaneous entry through the internal jugular or subclavian veins, or via the inferior vena cava with percutaneous entry through the femoral veins. Internal jugular or subclavian approaches are less susceptible to infection and are less restraining to the patient and thus are preferred for bedside management. The right internal jugular approach is preferred over left as it provides a direct route to the right atrium (RA). The subclavian approach is preferred via the left side, again due to ease of catheter flotation [1].

Central venous access is obtained as described in the previous chapter. Prior to flotation, the system should be appropriately leveled and zeroed. Usually attached to a manifold, the transducer is placed at the level of the mid-axillary line in the fourth intercostal space (the approximate level of the right atrium) and zeroed by opening the system to room air. Each port of the PA catheter is then carefully flushed and full inflation of the balloon is confirmed. An air leak should be excluded by dipping the balloon in a sterile bowl of saline. If the PA catheter is to be left in

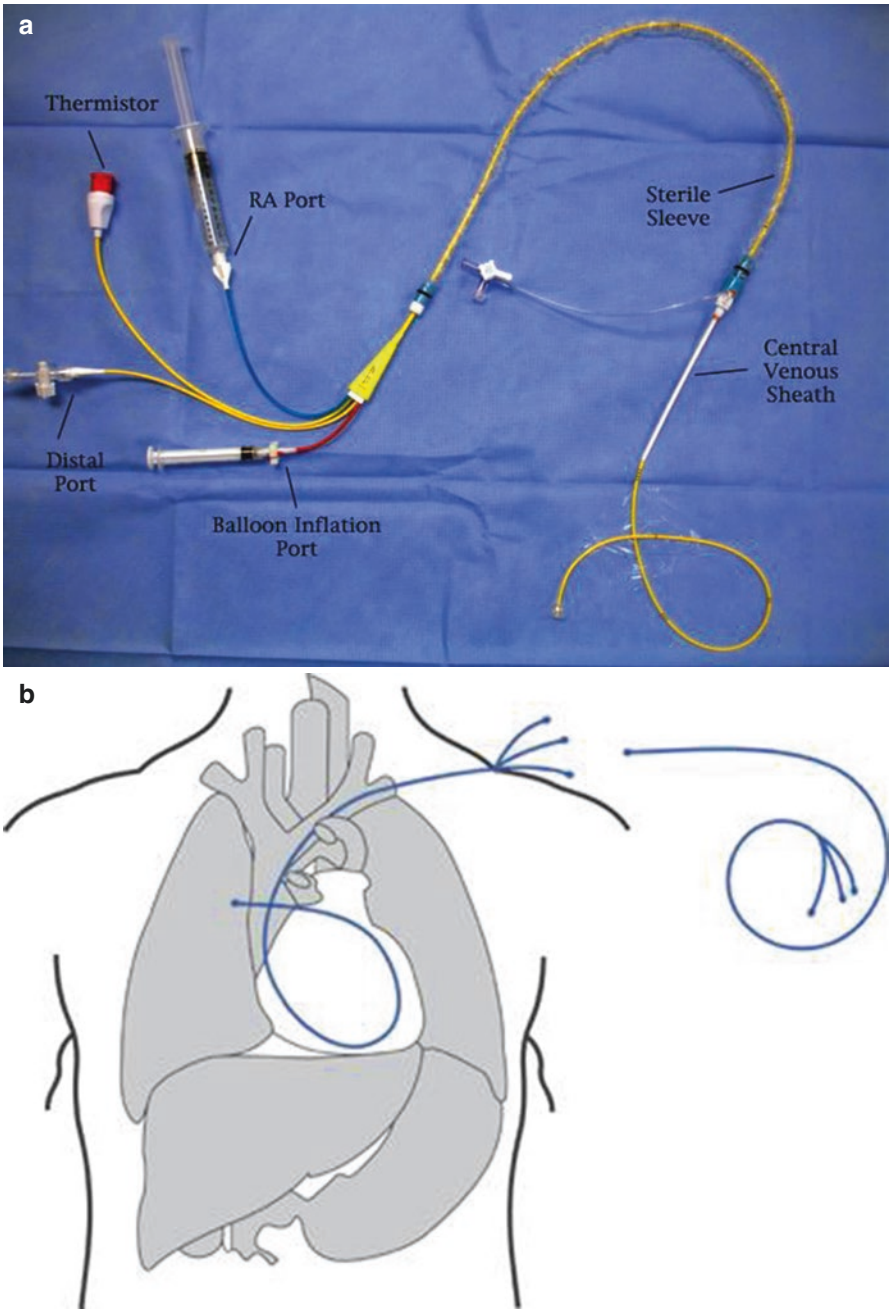

Fig. 14.1 (**a**) The pulmonary artery catheter. (**b**) A schematic showing the proper orientation of the pulmonary artery catheter when inserted through the left subclavian vein

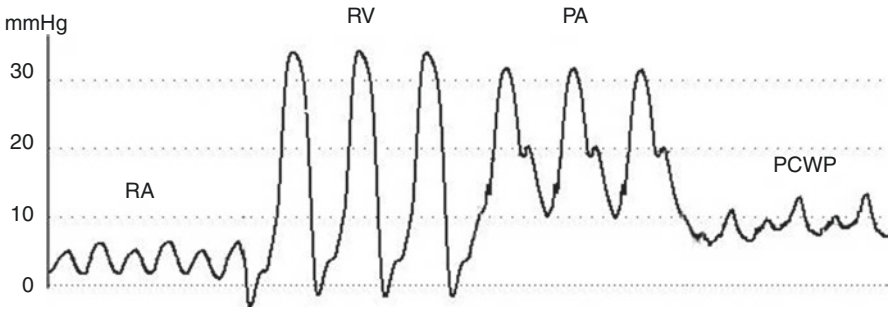

Fig. 14.2 Normal right heart pressure tracings. *RA* right atrium, *RV* right ventricle, *PA* pulmonary artery, *PCWP* pulmonary artery wedge pressure

place, it should first be inserted through a protective sterile sleeve. The PA catheter is then inserted through the central venous sheath to approximately 15 cm or until the RA waveforms are observed. The balloon is inflated and advanced gently. Fluoroscopy is used in the catheterization lab to direct placement; however, at the bedside, guidance is provided via the pressure waveforms (Fig. 14.2). Flotation of the PA catheter from the femoral vein is more difficult and usually requires fluoroscopic guidance [3, 4].

To minimize ventricular ectopy, the catheter should be passed rapidly through the right ventricle (RV) into the PA. From the PA the catheter is then advanced slowly to wedge position. In general, the PCWP tracing should be reached within 50–55 cm if the catheter is placed via the internal jugular or subclavian approaches. If the femoral approach is used, it should be reached at 65–70 cm. In cases of marked respiratory variation, the PCWP should be measured at end expiration. Once PCWP is recorded the balloon should be deflated and it should be verified that a clear PA tracing is obtained. The volume of air required to inflate the balloon for obtaining wedge should also be checked. If the volume is less than 1.5 cc, the catheter should be pulled back to avoid "over-wedging." In the catheterization lab, to evaluate for the presence of intra-cardiac shunts, screening blood samples are usually drawn for oximetric analysis from the RA and the PA. Oximetric analysis can also be performed to confirm accurate wedge position by obtaining a blood sample with a saturation of $\geq 95\,\%$ [3, 4].

The PA catheter can determine CO by two techniques – the thermodilution technique and using the Fick principle to measure oxygen consumption. In performing the thermodilution technique, a syringe with 10 cc saline is attached to the proximal port, whose tip is located in the RA when the thermistor on the distal tip is in the PA. The entire volume of saline is rapidly injected within 4 s in a single, smooth effort. The change in temperature as recorded by the distal thermistor is plotted over time and the area under the curve is planimetered to calculate CO (in liters/min). At least three serial thermodilution measurements should be performed and averaged (more if there is substantial variability). Factors that interfere with normal flow of saline past the sensing thermistor, such as low CO, tricuspid regurgitation, and intra-cardiac shunts (i.e., atrial septal defect) can affect the accuracy of CO determination [4, 5].

The Fick principle states that the total uptake or release of a substance by an organ is the product of blood flow to the organ and the arteriovenous (AVO_2) concentration difference of the substance [4]. Pulmonary blood flow (which is equal to systemic blood flow in the absence of a significant shunt) is determined by dividing oxygen consumption (the uptake of oxygen from room air by the lungs) by the arteriovenous oxygen difference across the lungs. Oxygen consumption can be measured by the use of a metabolic hood, but is routinely calculated based on body surface area. The AVO_2 concentration difference is calculated from the difference in arterial oxygen content ($1.36 \times \text{hemoglobin} \times AO_2$ saturation $\times 10$) minus the mixed venous (PA) oxygen content ($1.36 \times \text{hemoglobin} \times VO_2$ saturation $\times 10$). Thus CO can then be calculated:

$$\text{CO} = \text{O}_2 \text{ consumption}\left(\text{ml} / \text{min}\right) / \text{AVO}_2 \text{ difference}\left(\text{ml} / \text{L}\right)$$

Dividing the cardiac output by body surface area (m^2) allows the calculation of cardiac index (CI).

After the measurement of pressures and determination of CO have been completed, the pulmonary and systemic vascular resistance can be calculated using the following formulas:

$$\text{PVR} = \left(\text{MPAP} - \text{PCWP}\right) / \text{CO} \quad \left(\text{wood units}\right) \times 80 \left(\text{dynes} - \text{sec} - \text{cm}^{-5}\right)$$

$$\text{SVR} = \left(\text{MAP} - \text{RAP}\right) / \text{CO} \left(\text{wood units}\right) \times 80 \left(\text{dynes} - \text{sec} - \text{cm}^{-5}\right)$$

Where MPAP = mean pulmonary artery pressure (mmHg), PCWP = Pulmonary capillary wedge pressure (mmHg), CO = cardiac output (L/min), MAP = mean arterial pressure (mmHg), and RAP = right atrial pressure (mm Hg).

Data Interpretation

RA pressure The normal RA pressure ranges between 1 and 5 mmHg and under normal conditions decreases with inspiration. The *a wave* reflects atrial contraction and occurs just after the P wave on the surface ECG. Elevations of the *a wave* indicate resistance to RV filling, as can be seen in RV failure/infarction, pulmonic stenosis, or significant pulmonary hypertension. In atrial fibrillation the *a wave* is absent due to the lack of organized atrial contraction. The *x descent* follows and is due to RA relaxation and caudal recoil of the tricuspid valve during RV contraction. The *c wave*, which interrupts the *x descent*, results from bulging of the closed tricuspid valve into the RA during early systole. The *v wave* results from venous inflow into the RA during RV systole. It is prominent in tricuspid regurgitation and in increased flow, such as seen with atrial septal defect. The *v wave* is followed by the *y descent* that reflects the opening of the tricuspid valve. Prominent *y descent* can be seen in constrictive and restrictive states as a result of rapid atrial emptying into the RV [5].

Table 14.2 Normal hemodynamic values

SVO_2 0.6–0.75
CO 4–8 L/min
CI 2.5–4.0 L/min/M^2
RA 1–6 mmHg
RV 25/6 mmHg
PAP 25/10 mmHg
PCWP 8–12 mmHg
SVR 900–1300 dynes-sec-cm^{-5}
PVR 40–150 dynes-sec-cm^{-5}
MAP 70–110 mmHg

RV pressure The normal RV systolic pressure ranges between 15 and 30 mmHg and the RV end-diastolic pressure between 4 and 8 mmHg. The RV systolic pressure can be elevated by pulmonic valve disease or pulmonary hypertension. Abrupt elevation and plateau of the RV pressure in early diastole can indicate the presence of restrictive or constrictive physiology [3, 5].

PA pressure The normal PA systolic pressure is 15–30 mmHg and the PA end-diastolic pressure is 4–12 mmHg. Elevations in PA pressures are seen in pulmonary hypertension, left-sided heart failure, mitral valve disease, significant left to right shunt, and pulmonary disease (e.g., pulmonary embolism, chronic obstructive pulmonary disease) [5].

PCWP The normal mean PCWP is between 4 and 12 mmHg. The PCWP is an accurate measure of the left atrial (LA) pressure in the absence of pulmonary vascular disease. It approximates left ventricular filling pressures except in mitral stenosis and left atrial myxoma, where the LA pressure might be greater than left ventricular end-diastolic pressure (LVEDP). In acute aortic regurgitation, the LVEDP can be higher than the LA pressure. Elevation in mean PCWP is seen in left-sided heart failure, and mitral stenosis or regurgitation. Similar to the RA pressure, the PCWP has *a* and *v waves*, *x* and *y descents*. A prominent *v wave* suggests the presence of mitral regurgitation [5].

Normal hemodynamic values are summarized in Table 14.2.

Complications

Complications of RHC are rare, but can include pneumothorax/hemothorax, arterial puncture, bleeding, infection (including cellulitis at the insertion site, bacteremia, endocarditis and sepsis), venous thrombosis, arrhythmias (including ventricular arrhythmias and heart block/right bundle branch block), pulmonary artery rupture, cardiac perforation, air embolism, pulmonary infarction (if the balloon is left in wedge position too long), and knotting of the catheter. The duration of RHC should be minimized in order to avoid complications [3, 4].

Clinical Vignettes

Case 1

A 69 year old woman with history of dilated cardiomyopathy is admitted with pulmonary vascular congestion. She is treated with lasix and nitrates. However, further diuresis results in a creatinine rise despite signs of persistent volume overload.

RHC is performed with a BP 88/42 (57) mmHg, RA 14 mmHg, RV 52/7 mmHg, PA 54/25 (39) mmHg, PCWP 26 mmHg CO 2.7 L/min, CI 1.9 L/min/M2, and SVR 1275 dynes-sec-Cm-5. The phosphodiesterase inhibitor milrinone is initiated along with further diuresis for treatment of decompensated heart failure.

Case 2

A 54 year old man with history of ischemic cardiomyopathy and NYHA class III-IV heart failure is transferred to a tertiary care center for cardiac transplant evaluation. Echocardiography from the referring hospital showed diffuse global hypokenesis with an LVEF 15 % and was suggestive of pulmonary hypertension with a PA systolic pressure estimated at ≥70 mmHg.

RHC reveals RA 15 mmHg, RV 76/16 mmHg, PA 75/27 (45) mmHg, PCWP 21, CO 3.4 L/min, CI 1.8 L/min/M^2, and PVR 456 dynes-sec-cm^{-5} (5.7 wood units). To assess reversibility of pulmonary hypertension and appropriateness of cardiac transplantation, an infusion of nitroprusside is initiated in the cath lab and titrated gradually to 3.0 mcg/kg/min. Hemodynamic assessment is repeated with RA 12 mmHg, RV 62/12 mmHg, PA 60/19 (34) mmHg, PCWP 18 mmHg, CO 5.2 L/min, CI 2.9 L/min/M^2, and PVR 176 dynes-sec-cm^{-5} (2.2 wood units). Nitroprusside infusion demonstrates reversible pulmonary hypertension in this patient. Irreversible pulmonary hypertension (>4 wood units) remains an exclusion criteria for cardiac transplant as a normal donor RV will fail in the setting of high recipient PVR.

Case 3

A 75 year old woman with history of diabetes and hypertension presents to the emergency department more than 10 hours after onset of substernal chest pain. ECG reveals ST elevation and q waves in leads II, III, aVF suggestive of an evolving inferior myocardial infarction. Physical exam reveals a harsh holosystolic murmur along the left sternal border. During cardiac catheterization the patient became hypotensive requiring multiple pressors and insertion of an intra-aortic balloon pump. Cardiac catheterization reveals 100 % proximal right coronary artery occlusion. Successful percutaneous angioplasty and stent placement of the right coronary artery is performed.

After stent placement, RHC reveals RA 20 mmHg RV 43/21 mmHg PA 45/28 (37) mmHg PCWP 28 mmHg. Oximetric analysis revealed a large step-up in oxygen saturation from RA (47%) to RV (81%) suggestive of ventricular septal rupture. Transesophageal echocardiogram in the cath lab confirms rupture of the basal portion of the inferoposterior ventricular septum with left to right shunt flow. The patient is referred to cardiothoracic surgery.

Case 4

A 73 year old man with history of hypertension, chronic obstructive pulmonary disease, and atrial fibrillation is admitted for worsening shortness of breath and lower extremity edema. This is his third admission in 6 months for heart failure. Physical exam reveals elevated jugular venous pressure to the mandible, positive Kussmaul's sign (elevation of the jugular venous pressure with inspiration), and 2+ pitting lower extremity edema to the knees. Echocardiogram reveals left ventricular hypertrophy with mild aortic stenosis, normal left ventricular function and a small circumferential pericardial effusion.

RHC is performed with the following hemodynamic findings: RA 18 mmHg, RV 39/5 (18) mmHg, PA 37/18 mmHg, PCWP 18 mmHg, and LVEDP 18 mmHg. Simultaneous recording of right and left heart pressures show elevation and equalization of diastolic pressures and the RV and LV pressure tracings reveal a dip and plateau contour suggestive of constrictive physiology (Fig. 14.3). Subsequent CT of the chest demonstrates a thickened pericardium.

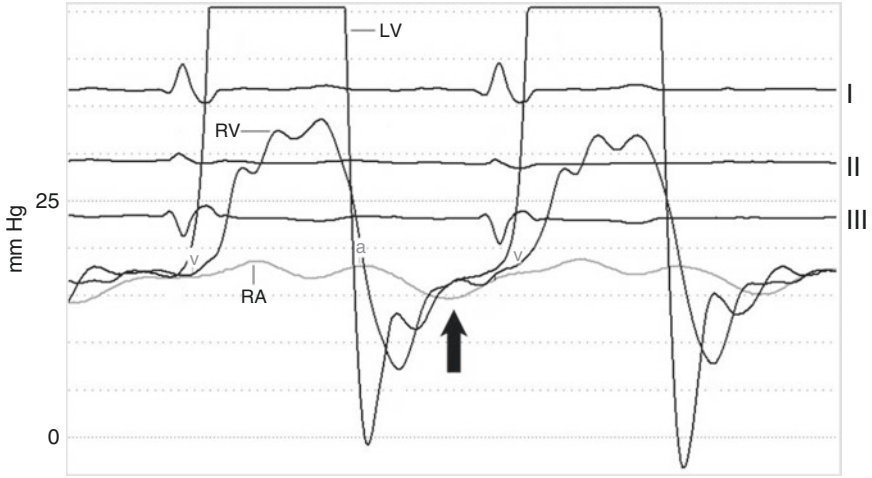

Fig. 14.3 Simultaneous right and left heart pressure tracing in a patient with constrictive pericardial physiology. Note the right atrial, right ventricular, and left ventricular diastolic pressures are elevated and equal (*arrow*). Right and left ventricular tracings show an early diastolic dip followed by a plateau as the non-compliant pericardium hinders ventricular filling in early to mid diastole—the "dip and plateau" sign. *RA* right atrium, *RV* right ventricle, *LV* left ventricle

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Chapter 15
Pericardiocentesis

Saleh Alshalash and Carey Kimmelstiel

Introduction

Evacuation of pericardial fluid from the pericardial space to treat cardiac tamponade was initially described in 1653 through surgical incision of the sternum [1]. Advancements in the technique were made with percutaneous needle aspiration in the nineteenth century and, currently, the procedure is done in a similar manner using small gauge needles and multi-modality imaging (echocardiography, fluoroscopy, or both). Cardiac tamponade is a clinical diagnosis and the size of the pericardial effusion required to cause tamponade depends on the rate of fluid accumulation.

Indications

1. Treatment of cardiac tamponade or prevention of impending cardiac tamponade in patients with moderate to large pericardial effusions and compromised hemodynamics.
2. Diagnostic aspiration to investigate the etiology of a pericardial effusion.
3. Invasive procedures in the pericardial space (epicardial ventricular tachycardia [VT] ablation or left atrial appendage [LAA] closure using the Lariat device)

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Contraindications

In a hemodynamically unstable patient there exist no absolute contraindications to pericardiocentesis. Uncorrected bleeding conditions is a relative contraindication to pericardiocentesis. Recurrent pericardial effusion may need surgical treatment with the creation of a pericardial window (communication between the pericardial and pleural spaces).

Equipment

Required equipment includes anti-septic solution, sterile drapes, gown and gloves, local anesthetic, a long small-caliber needle, syringes, alligator clip, guide wire, scalpel, stopcock, pigtail catheter, collection bag, ECG machine, and imaging modality of choice (echocardiography and/or fluoroscopy). Commercially available kits often include all of the needed equipment (Fig. 15.1).

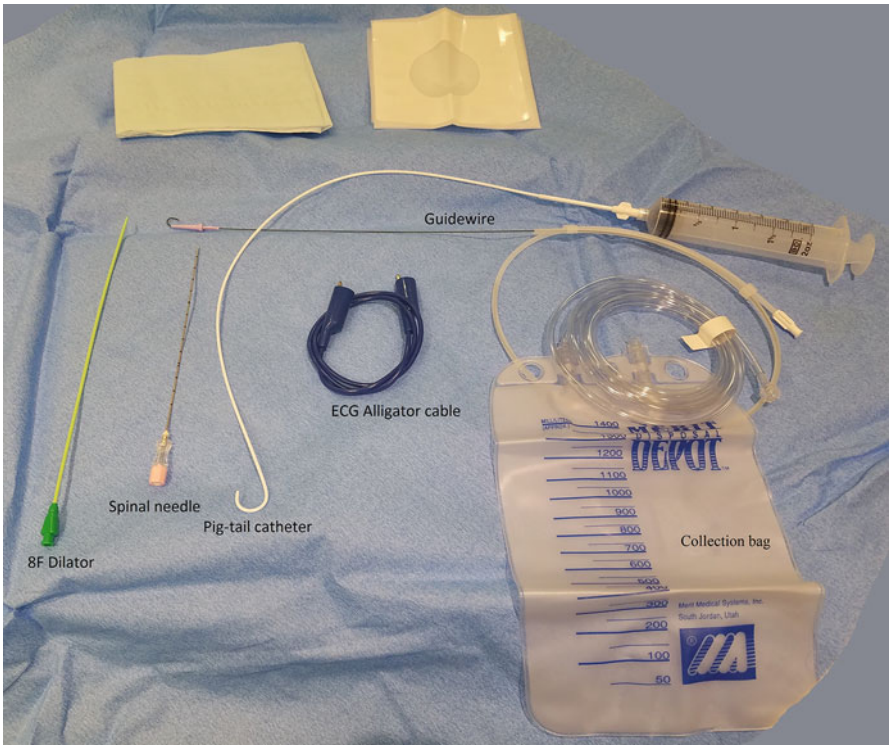

Fig. 15.1 Essential equipment for pericardiocentesis

Technique

There are three established methods to perform pericardiocentesis (Table 15.1). The most widely used is via a subxiphoid approach; other approaches include the apical and left parasternal approaches. The echocardiographic window helps in deciding which approach is most expeditious. Careful examination of the echocardiogram to "map the way" and choose which angle is needed prior to proceeding with pericardiocentesis, is an essential step.

To perform a pericardiocentesis from the subxiphoid approach, the patient is placed in a supine position usually lying on a wedge which elevates the torso to an angle of 30–45° which aids in accumulating the pericardial fluid anteriorly (Fig. 15.2). A sterile field is established. The skin and subcutaneous tissues are infiltrated generously with a local anesthetic. The needle is inserted at a shallow angle

Table 15.1 Summary of different approaches to pericardiocentesis

Approach	Advantages	Disadvantages
Subxiphoid	Can be done blindly without imaging in cases of emergency. Provides access to the anterior pericardial space. Furthest from pleural space	Possible injury to abdominal structures. Requires the presence of an anterior collection of fluid. Difficult in morbidly obese patients or patients with ascites
Apical	Provides access to the apical/posterior collection. LV wall is thicker than RV, therefore, injury may not result in perforation	Possible access to the pleural space, causing pneumothorax or injury to the LV apex (or LAD)
Left parasternal	Shortest distance from skin to pericardial space, access to the anterior pericardial space, avoids injury to abdominal structures	Possible injury to the internal mammary artery and entry into the pleural space

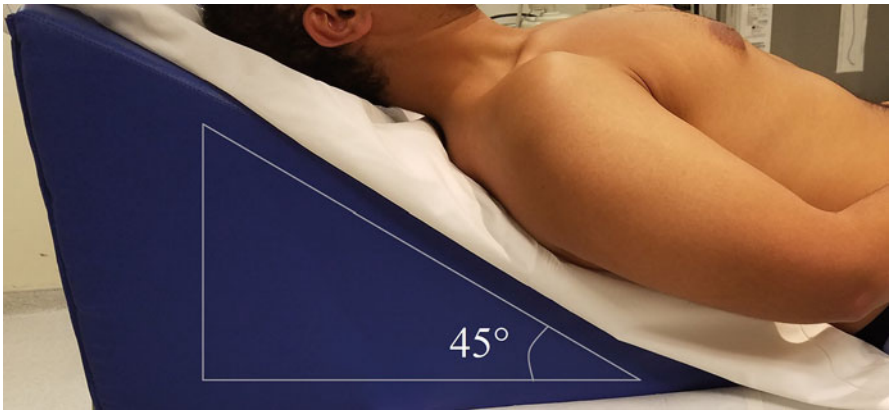

Fig. 15.2 A wedge is positioned underneath the patient to allow the free-flowing fluid to accumulate anteriorly

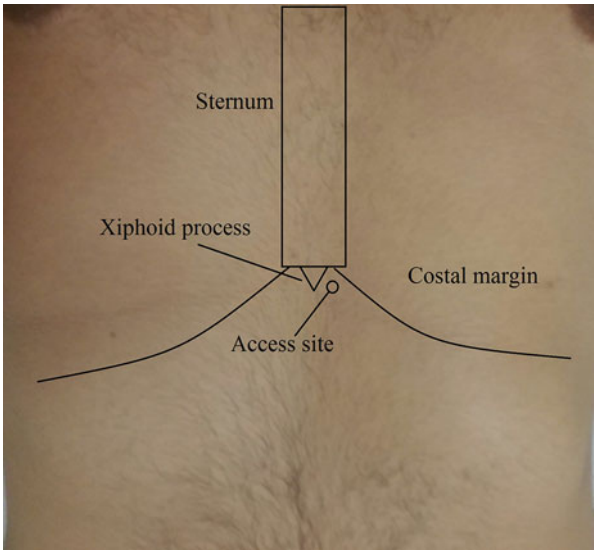

Fig. 15.3 Surface anatomy and landmarks to perform pericardiocentesis. Via the subxiphoid approach

just to the left of the xiphoid process immediately inferior to the costal margin (Fig. 15.3). The needle is advanced underneath the ribs, bevel up, while consciously making light contact with the overlying periosteum of the rib. This is done in an effort to avoid contact with the lung. The needle is directed towards the left shoulder. A "pop" can usually be felt when the pericardium is entered. At this time the trochar is removed and, if in the correct location, pericardial fluid will flow under pressure through the central lumen of the syringe. If no fluid is obtained, the syringe is removed and the process is repeated, usually with a slightly different angulation.

Currently, pericardiocentesis is rarely done with live echocardiographic guidance. However, some operators employ electrocardiographic (ECG) guidance in an effort to avoid ventricular perforation. An alligator clip is connected to an ECG lead. While slowly advancing the needle, the ECG is monitored, watching for ST segment elevation (a current of injury) which is indicative of contact with the thin-walled right ventricle. If seen, obviously the needle is withdrawn, the trochar removed and examination for pericardial fluid flow from the needle lumen is performed. If the operator is using fluoroscopy, then a guidewire is advanced through the needle, into the pericardial space and is visualized into the pericardium. If the operator is not sure that the wire is in the pericardial space, injection of a small amount of contrast may help in defining the position of the needle tip [2]. Using echocardiography to confirm placement involves injecting agitated saline into the pericardial space once the needle enters the pericardium and before the guidewire is inserted into the pericardial space. The agitated saline can be visualized in the pericardial space confirming the position of the tip of the needle (Fig. 15.4). If agitated saline is seen in a cardiac chamber the needle should be withdrawn. After passing the guidewire into the pericardial space, a dilator is advanced over the wire to create a tunnel through the subcutaneous tissues for passage of a pigtail catheter over the

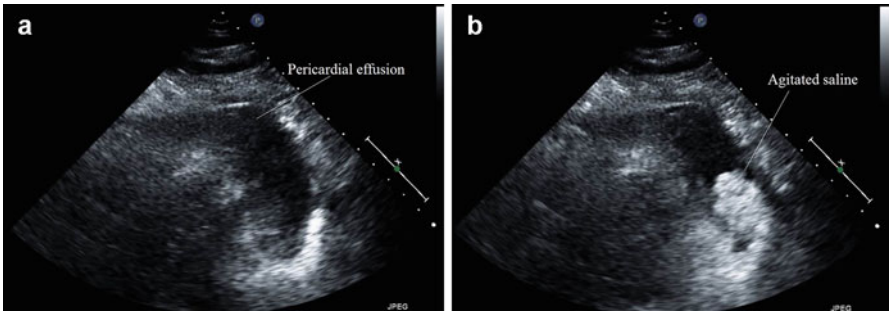

Fig. 15.4 (**a**) Modified apical view showing the pericardial effusion. (**b**) Agitated saline is seen entering into the pericardial space (*arrow*) confirming the correct position of the needle tip

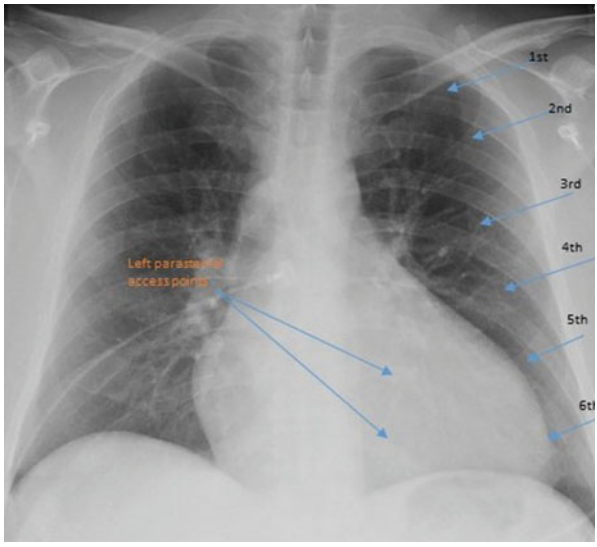

Fig. 15.5 Chest x-ray showing cardiomegaly. The anterior ribs are labeled on the CXR. Left parasternal access is in between the 4th-5th or 5th-6th ribs at ≥2 cm away from the edge of the sternum

guidewire. The guidewire is then removed from the pigtail catheter and a three-way stopcock is attached to the proximal end of the pigtail catheter.

Once the pigtail catheter has been placed, the opening pericardial pressure is recorded, fluid is then aspirated with usually 100 cc sent for laboratory analysis for cellular analysis and chemistries, usually for the determination of a transudate versus an exudate. Aspiration is performed until the operator is no longer able to withdraw any further fluid. At this time the total volume removed is recorded as is the closing pericardial pressure.

The left parasternal approach involves directing the needle almost perpendicularly to the chest (70–80°) often between the 5th and 6th ribs at least 2–3 cm lateral to the edge of the sternum to avoid injury to the internal mammary artery which runs 1–1.5 cm from the edge of the sternum (Fig. 15.5). Care must be taken to go over the rib to avoid injury to the neurovascular bundle which runs in the inferior aspect

of the ribs. Echocardiography is used to assess the depth of pockets and to estimate the angle and depth of tissue to enter into the pericardial space.

For the apical approach, the mid-clavicular line is identified in the fifth intercostal space then echocardiographic images are obtained and the point that has the best echocardiographic window is marked. The operator should make note of the angle of the probe as the needle should follow the same angle. The best access point should be the deepest pocket of fluid as well as that closest to the chest wall.

Data Interpretation

Pericardial fluid is sent to the laboratory for fluid analysis; tests are dependent on clinical presentation. The most widely used tests include total protein, glucose, LDH, and culture and sensitivity. Etiology of the effusion can be aided by the determination of whether the aspirated fluid represents a transudate or exudate. Other tests include cytology when there is clinical suspicion of a malignant process and antibody testing (ANA) when the clinical presentation is in keeping with a rheumatological/autoimmune process.

Complications

Possible complications include myocardial injury and puncture or laceration, coronary artery perforation, pneumothorax, laceration of the left lobe of the liver, injury to the phrenic nerve, and inability to access the pericardium requiring a surgical window. The damage resulting from inadvertently injuring structures can be minimized using multi-modality imaging, choosing the access site that has the easiest access to the largest collection of fluid. For example, a posteriorly located pericardial effusion might not be accessible percutaneously even though it is large enough to cause hemodynamic effects. Some have advocated that another way to minimize complications is to utilize a small caliber needle such as a micropuncture needle which is 21-gauge needle as compared to the standard 18-gauge needle. Using the 21-gauge micropuncture needle allows insertion of a 0.018-in. wire that is exchanged for a 4–5 Fr sheath that can accommodate the standard 0.035–0.038 in. guidewire.

Clinical Vignettes

Case 1

A 45-year old female with stage IV breast cancer presented with progressive shortness of breath. Her physical examination was remarkable for a heart rate of 110, a blood pressure of 90/60 mmHg, oxygen saturation 99% on room air and a respiratory rate of 22/min. Her heart sounds were muffled and jugular venous distension

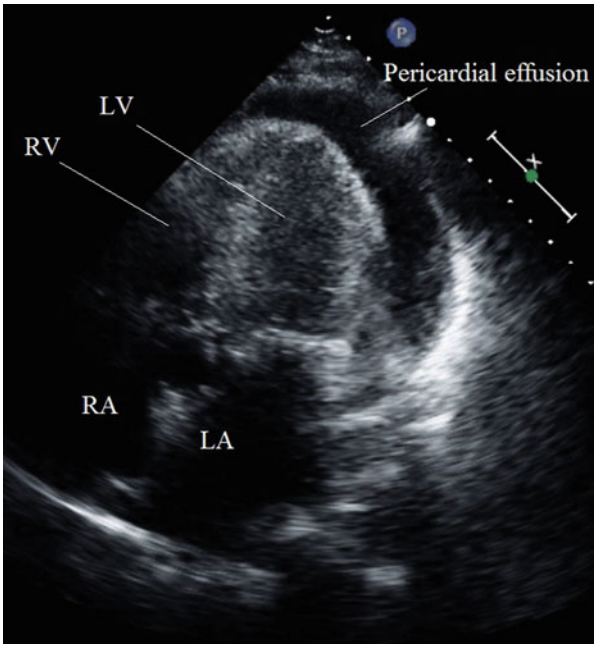

Fig. 15.6 Large circumferential pericardial effusion is seen in this apical four-chamber view. *LA* left atrium, *RA* right atrium, *LV* left ventricle, *RV* right ventricle

was present. Lung auscultation was not remarkable. Chest x-ray revealed cardiomegaly and normal lung parenchyma. Echocardiography documented a large pericardial effusion that was circumferential measuring 2.1 cm posteriorly in the parasternal long axis view, 1.8 cm at the apex in the four-chamber window, and 1.9 cm anteriorly using a subcostal window. Figure 15.6 depicts the apical five-chamber view showing the large pericardial effusion.

This pericardial effusion is most likely to be related to metastatic breast cancer and is accessible percutaneously via apical, left parasternal, or subxiphoid approach. Pericardiocentesis was performed, draining 725 cc of bloody fluid resulting in symptomatic improvement.

Case 2

A 29-year old female with untreated SLE presented with positional chest pain and shortness of breath. Physical examination showed a heart rate of 115 BPM, blood pressure 100/75 mmHg, oxygen saturation 98% on room air; Jugular venous distention was present. A 16 mmHg pulsus parodoxus was present. ECG showed sinus tachycardia, diffuse ST-segment elevation, and PR depression. Echocardiography documented a moderate-sized circumferential pericardial effusion with right atrial diastolic collapse. Right heart catheterization was performed and revealed the following pressures (mmHg): right atrium: 14, right ventricle: 50/14; pulmonary artery 45/14: pulmonary capillary wedge 14 mmHg; cardiac output 3.4 L/min; cardiac index 2.1 L/min $\times$ m^2.

The presence of tachycardia, low pulse pressure, echocardiographic evidence of diastolic chamber collapse, and low cardiac index demonstrate the hemodynamic sequelae of cardiac tamponade. Figure 15.4 shows the pericardial effusion with agitated saline injected into the pericardial space to confirm the position of the needle tip.

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Chapter 16
Procedural Sedation

Grace M. Wu

The American College of Emergency Physicians (ACEP) defines procedural sedation as "a technique of administering sedatives or dissociative agents with or without analgesics to induce a state that allows the patient to tolerate unpleasant procedures while maintaining cardiorespiratory function. Procedural sedation and analgesia (PSA) is intended to result in a depressed level of consciousness that allows the patient to maintain oxygenation and airway control independently."

The Joint Commission on Accreditation of Healthcare Organizations in the United States (JCAHO) has defined sedation as a continuum of consciousness: analgesia, minimal sedation, moderate sedation and analgesia (formerly termed conscious sedation), deep sedation and analgesia, general anesthesia, and dissociative sedation (Table 16.1).

Table 16.1 Continuum of depth of sedation: definition of general anesthesia and levels of sedation/analgesia

	Minimal sedation	Moderate sedation/ analgesia (conscious sedation)	Deep sedation/ analgesia	General anesthesia
Responsiveness	Normal response to verbal stimulation	Purposeful response to verbal or tactile stimulation	Purposeful response after repeated or painful stimulation	Unarousable, even with painful stimulus
Airway	Unaffected	No intervention required	Intervention may be required	Intervention often required
Spontaneous ventilation	Unaffected	Adequate	May be inadequate	Frequently inadequate
Cardiovascular function	Unaffected	Usually maintained	Usually maintained	May be impaired

Developed by the American society of Anesthesiologists; approved by the ASA House of Delegates October 13, 1999 [1]

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Indications

PSA may be used for any procedure in which a patient's pain or anxiety may be excessive and may impede successful completion of the procedure. Common cardiology procedures include electrical cardioversion, transesophageal echocardiogram, diagnostic and ablation procedures for cardiac arrhythmias, coronary angiography, transcutaneous valve replacements and repair, and insertion of implantable electronic device [2].

Contraindications

There are no absolute contraindications to PSA. Relative contraindications may include older age, significant medical comorbidities and signs of a difficult airway. In older patients, sedating agents should be given at a lower starting dose, using slower rates of administration and repeated dosing of medications at less frequent intervals. Patients with major comorbid medical conditions are at increased risk for adverse events however there is no evidence that alternative approaches (monitored anesthesia care or general anesthesia) are safer. PSA is relatively contraindicated in patients who are likely to be difficult to ventilate or oxygenate. Patients who have eaten recently are not contraindicated to PSA, however if a procedure is not emergent, the American Society of Anesthesiologists (ASA) recommends that the patient fast for 2 h after drinking clear liquids and 6 h after ingesting solid foods or cow's milk [1].

Equipment

Intravenous access should be established. Patients should have constant cardiac and respiratory monitoring, with careful monitoring of blood pressure, heart rate, respiratory rate, oxygen saturation, end-tidal carbon dioxide level and cardiac rhythm. Supplemental oxygen is often recommended to maintain oxygen levels during hypoventilation. In the event of respiratory compromise, equipment for performing endotracheal intubation and managing the airway should be readily available. Resuscitation medications, including medications for advanced life support and reversal agents should be available at bedside [1].

Technique

Ideal pharmacologic agents for PSA will have rapid onset and short duration of action, maintain hemodynamic stability and lack major side effects (Table 16.2). Some shorter procedures may be performed with the patient awake or only lightly

Table 16.2 Intravenous procedural sedation medications for adults

Medication	Initial dose	Onset	Duration	Repeat dose (as necessary)
Midazolam	0.02–0.03 mg/kg over 2 min; maximum 2.5 mg (1.5 mg maximum if elderly)	1–2.5 min	10–40 min	May repeat after 2–5 min
Fentanyl	0.5–1 mcg/kg	2–3 min	30–60 min	0.5 mcg/kg every 2 min
Propofol	0.5–1 mg/kg	0.5 min	5 min	0.5 mg/kg every 3–5 min
Etomidate	0.1–0.15 mg/kg	5–15 s	5–15 min	0.05 mg/kg every 3–5 min
Ketamine	1–2 mg/kg over 1–2 min	0.5 min	5–20 min	0.25–0.5 mg/kg every 5–10 min

Elderly patients are at increased risk of adverse events with these agents and dosing should be adjusted accordingly [3, 4]. See text for details

sedated with concomitant local anesthesia. Agents that depress cardiac function may be problematic during ablation of ventricular tachycardia. Pre-oxygenation should usually accompany sedative administration [1].

Benzodiazepines are commonly employed for their ability to produce anxiolysis and amnesia, however they have no analgesic properties. Midazolam is used most often due to its ability to penetrate the blood–brain barrier quickly. It can be used alone or in combination with short acting opioids (e.g., fentanyl). With repeat doses, midazolam can accumulate in adipose tissue and can prolong sedation. Care must be taken when using midazolam in the elderly, obese, and patients with renal or hepatic disease [2, 3].

Opioids are often administered alone or in combination with sedatives in procedures requiring PSA. Short acting agents such as fentanyl, alfentanil and remifentanil are used. Fentanyl rarely causes hypotension, however its primary side effect is respiratory depression, which is potentiated by the coadministration of sedatives.

Coadministration of midazolam and fentanyl is useful when ultrashort-acting agents (e.g., propofol) are unavailable. The combination of midazolam and fentanyl may cause hypoxia and apnea, and increase the need for airway intervention and medication reversal. It is suggested to administer midazolam first and fentanyl titrated carefully thereafter [2].

Propofol is an ultrashort-acting phenol derivative with highly lipophilic properties allowing it to cross the blood–brain barrier rapidly and therefore must be dosed carefully. It is an effective sedative and amnestic but provides no analgesia. Injecting propofol with lidocaine pretreatment or coadministration can prevent pain when injecting through intravenous catheter. Additional intraprocedural analgesia can be achieved by pretreatment with short acting opioids (e.g., fentanyl). Pharmacokinetics of propofol are unchanged in patients with impaired kidney or liver function. In older patients, the dose should be reduced by 20 % and be given slowly over 3–5 min. Propofol is contraindicated in patients with allergy to egg lecithin and soybean oil. Side effects include hypotension and respiratory depres-

sion in patients with severe medical problems (such as sepsis, cardiac dysfunction) or hypovolemia [3, 5].

Etomidate is an imidazole derivative that is commonly used for rapid sequence intubation but can be used for PSA as well. Lower doses should be used in patients with renal or hepatic impairment and in elderly individuals. Etomidate also has no analgesic properties and similar strategies to reduce pain can be used as with propofol. Myoclonus is the most frequently reported side effect (reported in up to 80 % of patients). In the event of severe myoclonus, immediate airway support and treatment with benzodiazepine (midazolam 1–2 mg IV, reduced every 60 s) are indicated. Other side effects include respiratory depression, adrenal suppression and nausea and vomiting [4].

Ketamine is a phencyclidine derivative that acts as a dissociative sedative, producing a trance-like state and provides sedation, analgesia and amnesia while preserving the airway. Ketamine is ideal for brief, painful procedures and for patients who may have a potentially difficult airway or have compromised respiratory function. Ketamine can cause disorientation, dream-like experiences, or hallucinations that can be treated with a small dose of midazolam. Other side effects of ketamine include nausea and vomiting, laryngospasm, tachycardia, hypertension, increased intracranial and intraocular pressure and hypersalivation. Ketamine has been associated with longer median times for return to baseline mental status and increased agitation during recovery [3].

Evaluation

In patients who are at risk of hypotension due to recent illness, dehydration, or cardiac disease, etomidate or ketamine is preferable to propofol. Patients who have potentially difficult airways to manage or have compromised respiratory function can undergo PSA with ketamine. All agents should be given at a lower starting dose with lower rates of administration and less frequent dosing intervals in elderly patients [3, 5].

Discharge Criteria

- Additional monitoring for complications inherent to the procedure is unnecessary
- Vital signs and respiratory and cardiac function should be stable and within acceptable limits
- Mental status and physical function should return to a point where the patient can care for himself or herself with minimal to no assistance
- Symptoms such as pain, lightheadedness and nausea should be well-controlled
- The person should be accompanied home by a reliable person who can provide support and supervision for at least a few hours [1]

Complications

PSA is largely considered safe as serious complications occur rarely. Complications can often be prevented through appropriate selection of patients, proper use of sedative medication and careful monitoring of sedation. The most concerning complication is dose dependent respiratory compromise causing hypoxia or hypercarbia, which develops in less than 1 % of cases. Naloxone (0.01–0.1 mg/kg IV or IM, max 2 mg) and flumazenil (0.01 mg/kg IV over 20 s, max 1 mg) may be utilized to reverse opioids and benzodiazepines, respectively. Significant hypotension and bradycardia may develop in patients with significant cardiac morbidity and patients receiving beta-blockers. Etomidate may be preferred in these settings. Additional adverse outcomes may include vomiting and aspiration, and inadequate sedation preventing completion of the procedure. Combined adverse event rate (adverse event and failure to perform procedure) occur 15 % of the time. Anesthesiology support should be readily available in high-risk patients [1].

Clinical Vignettes

Case 1

A 61 year old woman with a past medical history of hypertension, hyperlipidemia is diagnosed with new onset atrial fibrillation at her PCP's office. She undergoes DC cardioversion with midazolam and fentanyl without any complications. In the recovery area, the patient awakens, is oriented to person, place and time, and is communicative with nurses and staff. She is eating lunch.

While serious adverse events such as hypoxia rarely occur after discharge, it is common for patients to experience mild symptoms, such as nausea, lightheadedness, fatigue or unsteadiness for up to 24 h. A reliable person who can provide support and supervision should be present at the patient's home for at least a few hours [1].

Case 2

A 42 year old male with no past medical history presents after two episodes of syncope. He also reports episodes of lightheadedness that resolve spontaneously. All male members of his family died of sudden cardiac death at an early age. EKG reveals pseudo-right bundle branch block and persistent ST elevation in leads V1 to V2. Echo is unremarkable. The diagnosis of Brugada syndrome is made and patient is scheduled for placement of ICD under PSA with propofol. During the procedure, the patient becomes tachycardic and hypotensive. His SaO_2 drops to 82 %.

There are no reports of endotracheal intubation due to propofol induced respiratory depression during PSA. Mild hypoxia can usually be managed by interruption of the propofol and bag-mask ventilation (Fig. 16.1) [5].

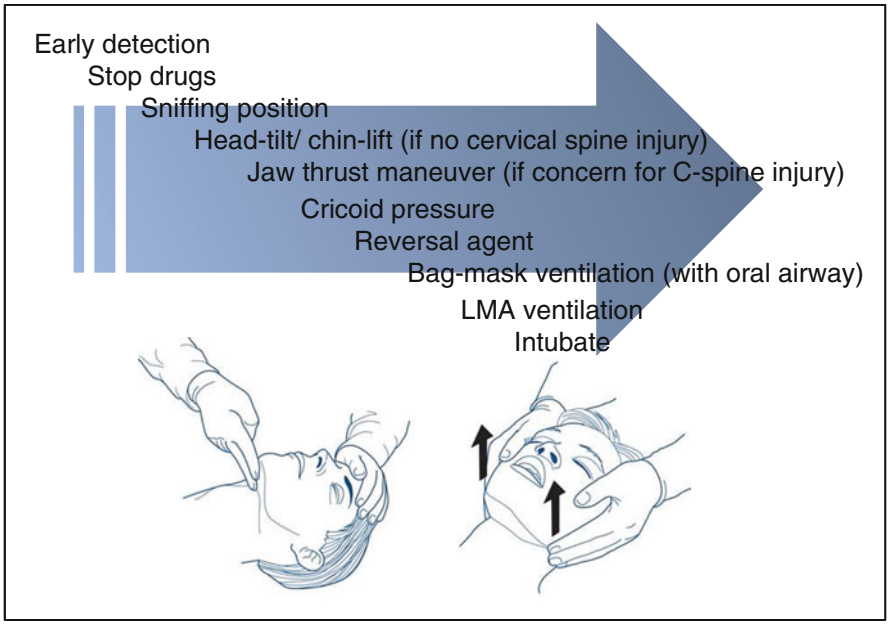

Fig. 16.1 PSA intervention sequence. Proceed down the intervention sequence as patient condition permits. (**a**) Head-tilt/chin-lift. (**b**) Jaw thrust maneuver involves thumbs on the maxilla pressing downward and four fingers posterior to the ramus applying upward pressure

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Chapter 17
Endotracheal Intubation

Aaron E. Brice

Endotracheal intubation is performed for airway protection or to permit mechanical ventilation. A flexible plastic tube is inserted through the mouth or nose and passed through the vocal cords into the trachea where it is secured in place. There are various situations where intubation is needed for patient care including both planned intubation and that done in an urgent or emergent context.

Indications

Specific indications for planned intubation include patients receiving general anesthesia, surgery in close proximity to the airway, or surgery in an atypical position. Indications for unplanned intubation can be broadly divided into several categories including respiratory failure, acute airway obstruction and loss of protective reflexes (Table 17.1) [1]. Rapid sequence intubation is the standard technique used in unstable patients that require prompt securement of the airway using the concurrent administration of a sedative agent for induction and a neuromuscular blocking agent for paralysis.

Table 17.1 Emergent indications for endotracheal intubation [1]

Respiratory failure	Pulmonary edema, excess secretions, atelectasis, acute respiratory distress syndrome, hypoventilation, neuromuscular failure
Acute airway obstruction	Laryngeal edema, laryngeal spasm, trauma, smoke inhalation, foreign body, hematoma, tumor, retropharyngeal abscess, epiglottitis
Loss of protective reflexes	Drug overdose, stroke, head trauma

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Contraindications

Endotracheal intubation may be employed as a life saving measure and in this circumstance there are few absolute contraindications to its use. However, clinicians must be mindful of conditions in which intubation may provoke additional problems. This includes blunt or penetrating trauma to the larynx causing laryngeal fracture or separation of tissue layers. Traction with a laryngoscope, stylet, or endotracheal tube may cannulate a false lumen or tear the airway. When there is significant doubt as to the safety of intubation noninvasive oxygenation and ventilation are preferred until a definitive or surgical airway can be created.

Relative contraindications to intubation include patients with a difficult airway. The mnemonic LEMON (Look, Evaluate, Mallampati Class, Obstruction/Obesity, Neck mobility) can be used to stratify a difficult airway [2]. Look externally for any clear visible evidence of potential problems such as micrognathia. Evaluate using the 3-3-2 rule (Fig. 17.1) to confirm that the mouth can open to fit 3 of the patient's fingers between upper and lower incisors, the submandibular space can fit 3 of the patient's fingers from chin to angle of the neck, and the space between the superior aspect of thyroid cartilage and angle of the neck can fit 2 of the patient's fingers. Mallampati class (Fig. 17.2) rates the space for oral intubation based on tongue size and degree of mouth opening from I (most open) to IV (least open). Obstruction and obesity assess any upper airway impediment caused by tumors, swelling, excess adipose tissue, or other masses. Neck mobility assesses the patient's ability to be placed in the sniffing position in which the head is elevated and neck extended forward.

Fig. 17.1 3-3-2 rule to evaluate the difficult airway. *1* Inter-incisor distance is three fingers. *2* Hyoid mental distance is three fingers. *3* Thyroid to floor of mouth is two fingers

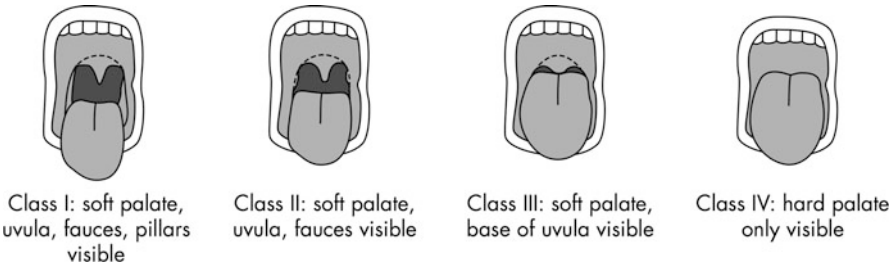

Fig. 17.2 Mallampati class I–IV

Equipment

Assembly of all necessary equipment prior to starting is essential as unforeseen complications may result in critical delays (Table 17.2).

Laryngoscopes are composed of a handle, blade, and light source. The two most frequently used blades are the Macintosh which is curved and the Miller which is straight. The choice of which to use is based on experience and personal preference [4]. These and other images of essential equipment are displayed in Fig. 17.3.

When there is difficulty visualizing the glottis a bougie or tube introducer is placed in the trachea and the endotracheal tube is passed over it. Oral and nasal airways are adjuncts and can be used to prevent the tongue from obstructing the posterior pharynx.

Endotracheal tubes are measured lengthwise in centimeters and by internal diameter in millimeters and French. Assemble tubes one size greater and one size smaller than the estimated tube to be used. Most adults will need at least an 8.0 mm tube but an inappropriately small tube will increase the work of breathing and if a bronchoscopy is to be performed the tube must be sufficiently wide to allow passage of equipment.

Pharmacologic agents for rapid sequence intubation are given IV push and include both a sedative agent for induction and a neuromuscular blocking agent for paralysis. Commonly used sedative agents with dosing listed in mg/kg include midazolam (0.3–0.35), etomidate (0.2–0.6), propofol (2.0–2.5), and ketamine (0.5–2.0). Rapid paralysis with dosing listed in mg/kg is frequently achieved with succinylcholine (1.0–1.5), rocuronium (0.6–1.2), atracurium (0.4–0.5), and vecuronium (0.08–0.1).

Table 17.2 Essential equipment [3]

Face mask with bag valve	Bougie
100 % oxygen	Sedative agent
Oral and nasal airways	Neuromuscular blocking agent
Suction device with catheters	Local anesthesia
Laryngoscope with handle and blades	Syringe to inflate endotracheal cuff
Endotracheal tubes with stylet	Tape

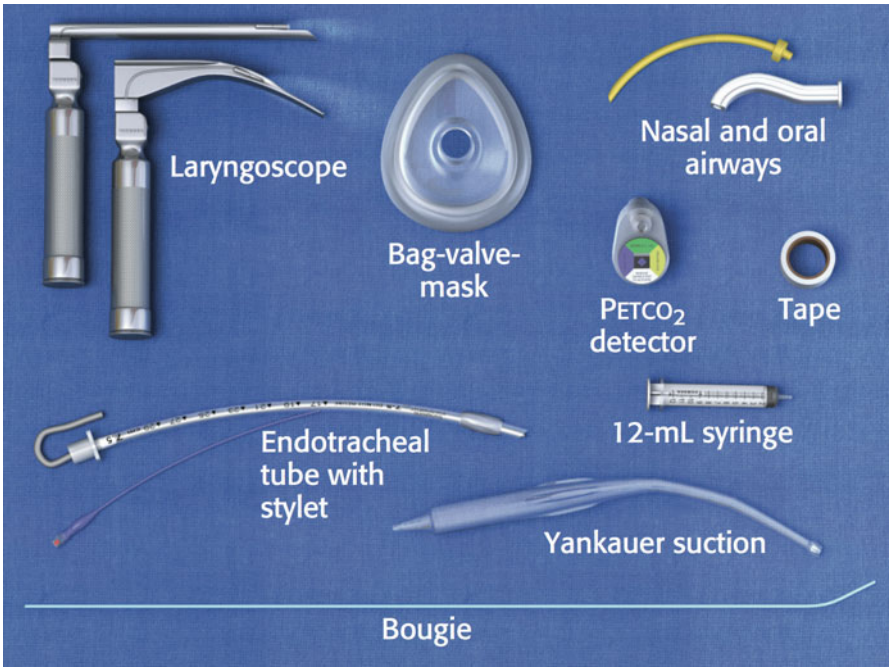

Fig. 17.3 Essential equipment for endotracheal intubation

Technique

Successful intubation begins with the pre-procedural evaluation but in an emergency some aspects must be omitted. Stepwise technique of rapid sequence intubation can be remembered with the "Seven P's" (Preparation, Preoxygenation, Pretreatment, Paralysis and induction, Protection/Positioning, Placement, and Postintubation management) [5].

Preparation evaluates the airway, gathers supplies, and ensures the patient is connected to required lines and monitors. Preoxygenation with 100 % high flow oxygen with saturation monitoring for 3.5–4 min will replace nitrogen in the patient's functional residual capacity with oxygen and increase the time intubation may be attempted during apnea. Pretreatment with lidocaine or fentanyl may be used to decrease natural coughing and gagging reflexes during intubation. Paralysis with induction uses administration of sedative and neuromuscular blocking agents concurrently by IV push to achieve unconsciousness and muscular flaccidity. Protection to prevent aspiration consists of applying cricoid pressure with Sellick's maneuver causing posterior compression of the cricoid cartilage against the vertebral body to lessen the diameter of the hypopharynx. Placement of the tube requires the laryngoscope to be held in the left hand and the gloved right hand opens the mouth by simultaneously pressing the thumb

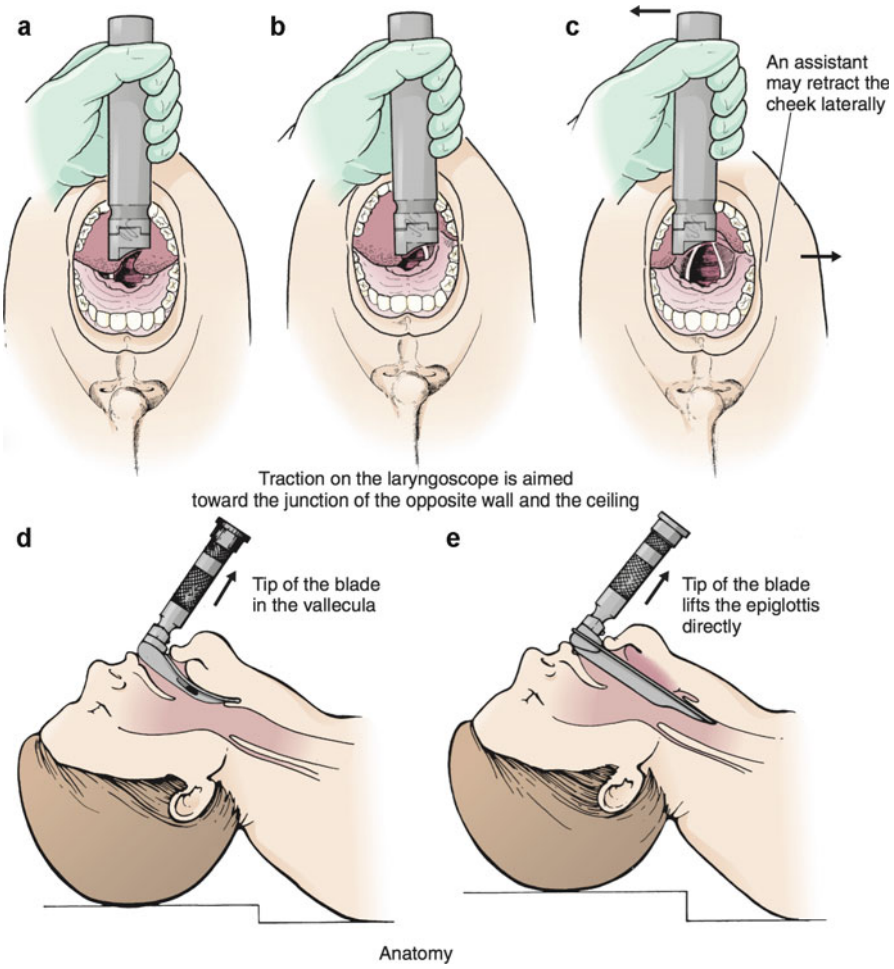

Fig. 17.4 Direct visualization of vocal cords. (**a**) Blade is under middle of tongue and obscuring the glottis. (**b**) Tongue not far enough left and obscuring the glottis. (**c**) Correct blade placement with tongue elevated and to the left. (**d**) Use of curved (Macintosh) blade. (**e**) Use of straight (Miller) blade

against lower incisors and index finger against upper incisors in a scissor motion. The blade is inserted in the right mouth and in a sweeping motion moves the tongue to the left (Fig. 17.4). The epiglottis is visualized and the blade is advanced to this point and then elevated forward in a straight line at a 45° angle to reveal the vocal cords avoiding contact with teeth to prevent trauma. Direct visualization of the vocal cords is obtained, the tube is passed through them, the cuff inflated, stylet withdrawn, and correct position of the tube is confirmed. Postintubation management involves securing the tube, adjusting ventilator settings, and post-procedure monitoring.

Data Interpretation

Potentially difficult mask ventilation may be recognized in patients that are body mass index greater than 26, age 55 or older, edentulous, or with significant facial hair. If these factors are encountered intubation performed while the patient is awake with local anesthesia may be preferred.

During preoxygenation when high flow oxygen is used and saturation cannot be maintained greater than 93 % positive pressure ventilation may be employed. If saturation is persistently less than 91 % manual ventilation may be necessary.

Tube placement is measured from lips to distal tube and in average sized adults is at the 23 cm line for males and 21 cm line for females. Correct tube placement is determined by visualizing bilateral symmetric expansion of the chest and checking for breath sounds in both lungs and an absence of sound over the stomach. End-tidal carbon dioxide measured by calorimetric detection or standard capnography can be used to confirm tracheal placement. A chest xray shows the degree of tube depth and the distal tube should rest approximately 3 cm above the carina.

Cuff pressure should be 15–30 mmHg and below the approximate capillary pressure of 32 mmHg. The use of a low pressure, high volume endotracheal tube cuff will reduce the chance of ischemic injury caused by tissue compression.

Complications

Trauma from the laryngoscope, stylet, or endotracheal tube may damage the airway or surrounding soft tissue. Nontraumatic complications including bronchospasm, hypoxia, and aspiration of stomach contents can also occur. Significant cardiovascular events including ventricular tachycardia and ventricular fibrillation are not common but may warrant antiarrhythmic prophylaxis in patients with previous arrhythmias or myocardial ischemia. Stimulation of the laryngeal branches of the vagus nerve may cause bradyarrhythmias that are responsive to atropine. Mechanical ventilation may cause hypotension from decreased venous return due to elevated intrathoracic pressure. Initial management consists of bolus intravenous fluids and evaluation of airway pressures but more serious alternative causes of hypotension including myocardial ischemia and pneumothorax must also be considered. When intubation is prolonged patients are predisposed to a number of potential problems including tracheomalacia, tracheal stenosis, and tracheal erosion (Table 17.3) [3].

Table 17.3 Complications from endotracheal intubation [3]

Intraprocedural complications	Aspiration
	Airway perforation
	Laryngospasm
	Trauma to dentition or airway
	Spinal cord injury
	Epistaxis
	Ventricular tachycardia
	Bradycardia
	Endotracheal tube blockage
	Tube dislodgement
	Bronchus intubation
Postprocedural complications	Laryngitis
	Laryngeal edema
	Hypoglossal nerve compression
	Ulceration of airway mucosa
	Vocal cord paralysis
	Tracheal stenosis
	Laryngeal granuloma
	Pneumothorax

Clinical Vignettes

Case 1

A 68-year-old man is admitted to the hospital for 1 week of worsening shortness of breath. He has a medical history of heart failure with an ejection fraction of 30 % and takes metoprolol, enalapril, and spironolactone at home. On physical exam he is afebrile, blood pressure is 82/50, heart rate is 108, respiratory rate is 32 and he is satting 86 % on 70 % oxygen from a nonrebreather mask. He does not know where he is or the year and attempts multiple times to remove his oxygen mask. His lungs have bilateral rales and cardiac auscultation elicits an S3 heart sound. Arterial blood gas reveals pH 7.48, pCO_2 32 mmHg, and pO_2 58 mmHg. His chest xray shows cardiomegaly, bilateral pleural effusions, and alveolar edema.

This patient has acute decompensated heart failure with evidence of cardiogenic shock and requires timely endotracheal intubation and mechanical ventilation. He is in respiratory distress and must be stabilized. There is no role for noninvasive ventilation given his current hemodynamic instability. Other contraindications to noninvasive ventilation include altered mental status, increased risk for aspiration, facial trauma, severe obesity, respiratory arrest, myocardial infarction, and arrhythmias.

Case 2

A 42-year-old man is found unresponsive in the street next to an open bag of unmarked white powder. Paramedics intubate him on the scene and transfer him to the emergency department. When he arrives he is unresponsive to verbal stimuli but sternal rub elicits a deep groan. He is afebrile, blood pressure is 98/66, and heart rate is 115. Oxygen saturation is 84 % on 80 % inspired oxygen. He has reduced expansion of the left side of his chest with reduced breath sounds on the left. The endotracheal tube depth is 29 cm. Cardiac exam is unremarkable. Blood glucose is 94 and his cardiac biomarkers are pending. Electrocardiogram shows nonspecific ST and T wave changes.

This patient has right mainstem bronchus intubation due to excess endotracheal tube advancement and is likely suffering from drug overdose. His low oxygen saturation can be fixed by withdrawing the tube to a depth of 23 cm in this male patient. Intubations in the field are more difficult and prone to more frequent complications given the uncontrolled environment. Correct tube placement must always be checked by verifying appropriate tube depth, visualizing symmetric chest excursion, auscultating bilateral breath sounds, measuring end-tidal carbon dioxide, and obtaining a chest xray showing tube depth.

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Part III
Electrophysiology

Chapter 18
The Electrocardiogram

Alexis P. Rodriguez

Introduction

The invention of the electrocardiogram (ECG or EKG) dates back to the eighteenth century when Luigi Galvani realized that muscular activity could be induced with the exposure to an electric field. However, the term itself was not used until the end of the nineteenth century by Willem Einthoven. Throughout the years, the ECG has continued to evolve, especially in the tracing recording portion, but has never lost its great clinical meaning [1].

The physical principle is the recording of physical activity of the heart using skin electrodes, which detect cardiac myocytes depolarization and repolarization waves. In general, a positive depolarizing wave that travels towards the electrode creates an upward deflection in the paper tracing. Conversely, any wave traveling away from the electrode is recorded as a negative deflection. Finally, the amplitude, duration, and direction of any deflection depend on that of the electric vector.

Indications

The opinion on ECG indications varies between physicians depending on the patient and the clinical indications. Nonetheless, it is generally accepted that this test aids in the diagnosis of overt or suspected cardiovascular disease with follow up recordings if there is a change in clinical status. It is also generally accepted for initial evaluation in high-risk individuals, i.e., older than 40, history of dyslipidemia, hypertension, or other risk factors. Furthermore, there is a role in the perioperative

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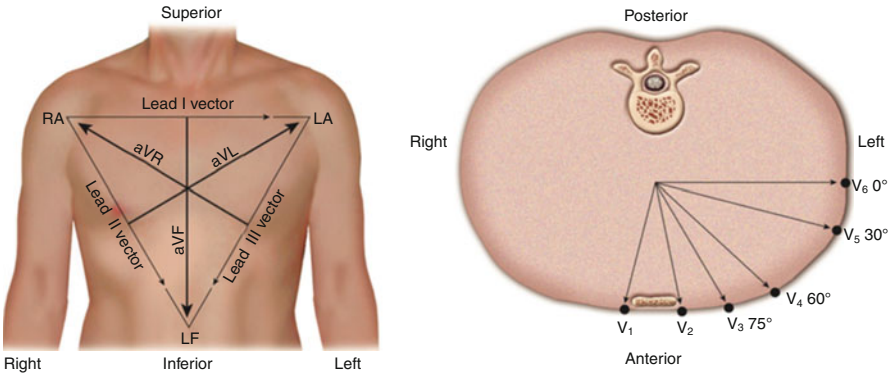

Fig. 18.1 Lead vector for the three standard limb leads, the three augmented limb leads (*left*), and the six unipolar precordial leads

setting whether for initial evaluation prior to surgery or afterwards to monitor for complications. Selected individuals, albeit healthy otherwise, benefit from routine screening ECGs; these include, athletes, pilots, bus drivers, among others [2].

Equipment and Technique

Cardiac potentials are detected by electrodes placed throughout the torso in specific arrangements to form the different types of ECG leads (Fig. 18.1). These leads record the potential difference between two electrodes, the positive and negative. There are three standard limb leads, three augmented limb leads, and six precordial leads for a total of twelve leads. Other systems have expanded to other leads to detect right precordial leads to detect right ventricular abnormalities, or left posterior leads to detect acute posterolateral infarctions.

Technique

The patient is initially asked to lie supine and relax as much as possible. The chest is exposed so that there is no interaction with lead placement, but recognizing that patient's privacy should be maintained at all times. Figure 18.2 reveals the anatomic landmarks for lead placement. These areas should be identified and cleaned to ensure appropriate electrode placement and contact with the skin. ECG recorders have specific manufacturer's instructions. Nonetheless, beforehand, it is crucial to determine if there are any possible issues that may interfere with the accurate recording, i.e., electrical calibration, signal interference, wandering baseline, among others.

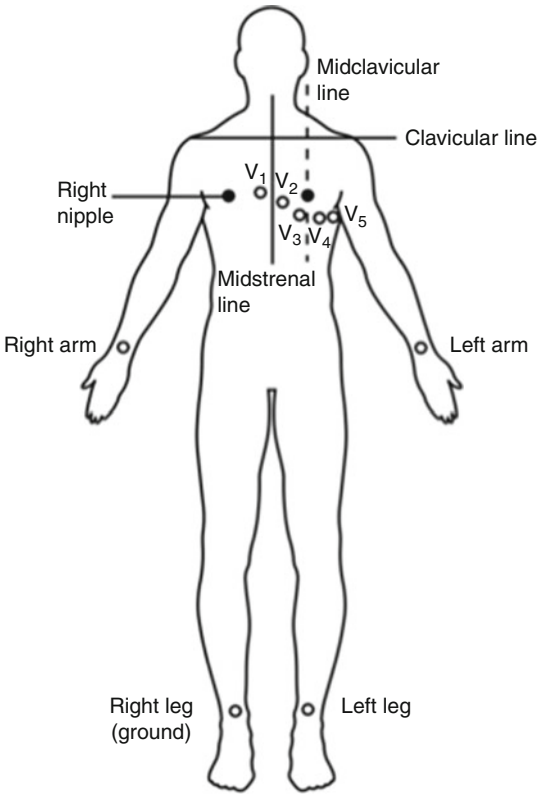

Fig. 18.2 ECG lead placement

Data Interpretation

Most ECGs are recorded on standard settings at 25 mm/Section (X Axis) and 10 mm/mV (Y axis). Different settings can be obtained depending on the heart rate, or voltage. Before attempting to interpret an ECG, the reader should pay close attention to the standardization. For ease, this can generally be found at either the left or right sides of the tracing.

The normal ECG is composed of multiple waves and intervals, which represent the different portions of the cardiac cycle (Fig. 18.3). The P wave, representing atrial activation is best appreciated in lead II or V1. The PR segment is usually an isoelectric segment that begins at the end of the P wave and ends with the QRS. Depression of the P wave is associated with pericardial disease. Ventricular activation ensues with a number of complex interactions, which are recorded as a set of deflections that give rise to the QRS. The T wave represents ventricular repolarization [3]. The QT interval is measured from the last portion of the QRS to the end of the T Wave, and represents a measure how fast the ventricles repolarize. A prolonged QT constitutes a marker for potential ventricular tachyarrhythmias. Since

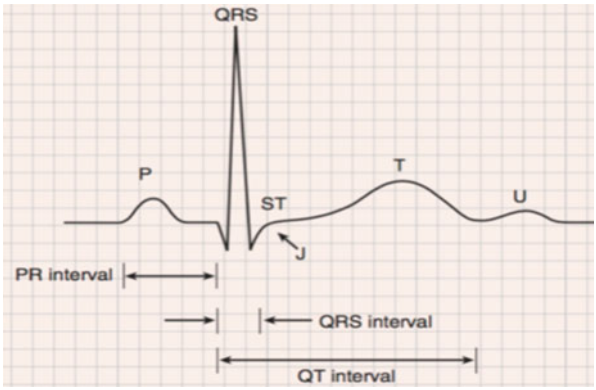

Fig. 18.3 The waves and intervals in a normal electrocardiogram

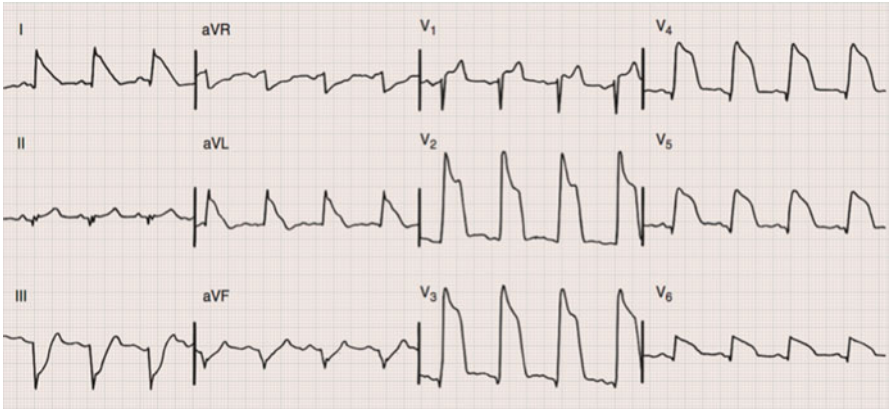

Fig. 18.4 Case 1

the QT measurements vary with heart rates, a standardized measurement, the QTc, is preferred at times. Different formulas have been derived. The Bazett equation calculates the QTc by dividing the QT by the square root of the RR interval. The Firderecia method uses the cube root. Other more complex methods, including regression analysis exist but are beyond the scope of this book.

Clinical Vignettes

Case 1

50 year-old gentleman with history of hypertension and dyslipidemia presents to the emergency department referring crushing chest pains for the last 25 min. The ECG is shown in Fig. 18.4.

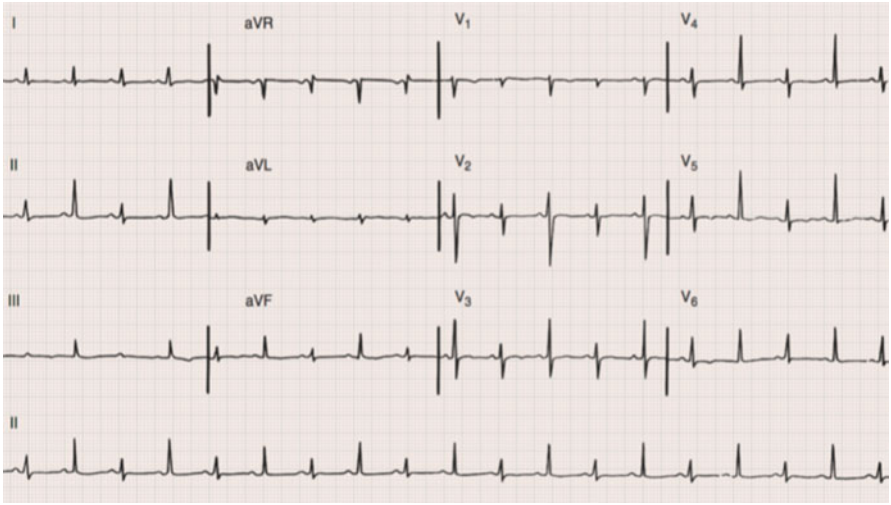

Fig. 18.5 Case 2

This ECG is representative of the acute phase of an extensive anterolateral ST-elevation myocardial infarction (STEMI). There is marked J point and ST-segment elevation along prominently tall and broad T Waves. STEMIs are generally accompanied by ST reciprocal depressions in the opposite leads, in this case these are noted in III and aVF. A particular case is the inferior STEMI. In this setting, the presence of right ventricular infarction should be evaluated by the use of, RV leads (VR3, VR4, VR5, and at times VR6). STEMIs represent a medical emergency that requires expedited intervention. In this particular patient, the culprit lesion is most likely located in the right coronary artery. The best benefit is derived from early aggressive intervention within 90 min of patient's arrival to the hospital necessitating the need to obtain the ECG within 10 min of emergency department arrival.

Case 2

24 year old man brought to the Trauma Center after being involved in an unrestrained motor vehicle head-on collision. Notes severe chest pain at the airbag site of impact. On arrival to the hospital, he is tachycardic, tachypneic, and diaphoretic. His initial ECG is shown in Fig. 18.5.

This patient has experienced major trauma to the chest. His symptomatology, vitals, and ECG are suggestive of a large pericardial effusion with tamponade. The ECG reveals a sinus tachycardia, with low QRS voltages, which demonstrated electrical alternans, a marker of a large pericardial effusion. This diagnosis should prompt evaluation with a complete echocardiogram to determine if tamponade physiology is present.

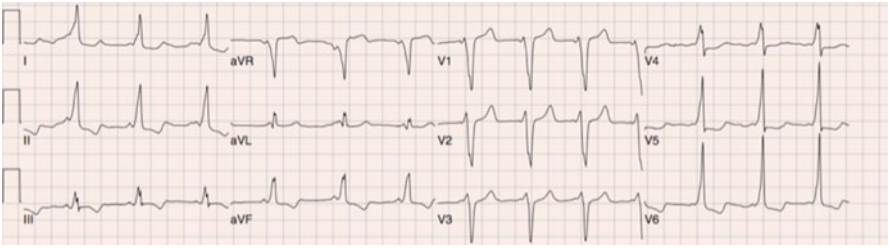

Fig. 18.6 Case 3

Case 3

18 year-old football player that complained during practice of palpitations comes to the office with the EKG shown in Fig. 18.6

This patient presents with an EKG that reveals preexcitation. These pathways have a unique ECG pattern with a slurred initial upstroke of the QRS and a short PR interval. Note the early upright QRS deflections in leads I, II, and aVF, and negative in aVR and the rS pattern in V1 and V2. The Wolff-Parkinson-White (WPW) syndrome, a type of preexcitation, occurs with the presence of such accessory pathways and tachycardia.

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Chapter 19
Ambulatory Electrocardiography

Douglas W. Laidlaw and N.A. Mark Estes III

Introduction

Ambulatory electrocardiography (AECG) refers to diagnostic techniques used to record cardiac rhythm in an outpatient setting. AECG methods provide a recording of the cardiac rhythm from one or more leads for durations that are variable but can be up to several years [1–3]. AECG techniques permit evaluation of dynamic cardiac electrical activity that is frequently intermittent and of short duration. Over the last several years, new technologies have emerged that allow use of multiple types of noninvasive and invasive recorders for AECG.

Historically, continuous ambulatory recorders, commonly referred to as Holter monitors, were developed to record the ECG continuously for a period of 24 h. The continuous AECG is most commonly performed in patients with symptoms that occur once daily or more frequently. Contemporary Holter monitoring devices have time markers and patient-activation indicators. The recorded digital data are analyzed after completion of the monitoring by computer with technical oversight. Current Holter monitoring technology does not allow for remote transmission of the data from the patient for analysis. Typically a Holter monitor report includes information about the total number of heart beats, average heart rate, maximum and minimum heart rate, number of premature atrial and ventricular beats, tachyarrhythmias, ST segment changes, and patient reported symptoms and the associated recordings of the patient's rhythm.

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Short-term event monitors are small, pocket-sized, recorders that are carried with the patient and applied to the skin with electrodes when the patient experiences symptoms. In addition to the typical hand-held device, wrist-watch units are also available. The major advantage to event monitors is that they allow the patient to be free from wearing electrode patches, which are often inconvenient and irritating. However, because the device is not continuously recording the ECG, any symptom or arrhythmia must last long enough to permit activation of the recorder. Current short-term event monitors are capable of transmitting digital data remotely for analysis. However, because these devices have a low diagnostic yield when compared to other available AECG techniques, they are not commonly used clinically. Typically the short-term event monitors given information regarding the patient's rhythm at the time of symptoms

Noninvasive "loop monitors" are capable of recording the patient's ECG for several days, weeks, or months monitors the ECG continuously with hard wiring to electrode patches. Historically these devices are called loop monitors because these devices continuously looped their recording tapes. These devices are used for patients with less frequent symptoms that would not be expected to be captured with Holter or event monitoring. They are commonly used for 2–4 weeks or longer. This form of AECG monitoring is typically activated by the patient by triggering the device to store the cardiac rhythm for up to several minutes. The cardiac rhythm is stored prior to, during, and after symptoms onset. Recordings can then be transmitted remotely for evaluation. These devices also can be automatically triggered to record based on pre-specified parameters of heart rate including irregularity. Most commonly, these devices are programmed to automatically detect bradycardic arrhythmias, tachyarrhythmias, and atrial fibrillation [4].

Some noninvasive loop monitors have the capacity to record all cardiac rhythms in a full disclosure fashion continuously for weeks and transmit data remotely. These real-time continuous cardiac monitoring systems are the newest form of event monitors and overcome the many limitations of Holter, event monitors and standard loop monitors. They are worn continuously and automatically record and transmit arrhythmic event data from an ambulatory patient remotely. This type of recorder is commonly referred to as mobile outpatient cardiac telemetry [5]. Like the event recorders transmission can triggered based on parameters of heart rate and by patient triggered symptoms. These monitors have the capacity similar to event recorders to transmit remotely. This type of AECG is being use more commonly as the diagnostic yield is higher than other forms of monitoring.

Occasionally a non-invasive evaluation for symptoms does not provide a diagnosis using the above techniques. Under these circumstances long-term implantable loop recorders (ILR) are currently available [6]. These devices are typically implanted in the left pectoral region as a simple outpatient procedure. Similar to the noninvasive loop monitor, the implantable loop monitor can be activated by the patient at the time of symptoms. ILRs record the patient's cardiac rhythm prior to, during, and after a patient triggered event. It also will record the cardiac rhythm automatically when the heart rate or rhythm falls outside of predetermined parameters for low and high heart rates. Recent technology allows reliable detection of atrial fibrillation, distinguishing it from other rhythms with a high sensitivity and specificity. Current devices have battery longevity expected to approach 3 years.

Indications

The most common indication for ambulatory monitoring is assessment of cardiac arrhythmias or conduction abnormalities as the cause for symptoms such as palpitations, pre-syncope or syncope. Ambulatory monitoring is also indicated for risk stratification of patients with multiple types of cardiovascular disease. It is also used for evaluation of therapy and for the detection of silent ischemia. The choice of recording technique depends on the patient's symptoms and the indication for the test (Table 19.1).

Indications for AECG are summarized in the ACC/AHA Guidelines for Ambulatory Electrocardiography [2]. Common indications for its use include palpitations, unexplained syncope, and ischemia detection in patients with suspected variant angina (Table 19.2). In addition, AECG may be utilized in special circumstances for antiarrhythmic drug monitoring and the assessment of pacemaker and Implantable Cardioverter-Defibrillator (ICD) function (Table 19.3). Other indications for ambulatory monitoring include assessment of the average heart rate and adequacy of rate control in patients with atrial fibrillation. Increasingly, techniques of ambulatory monitoring are being used to evaluate for otherwise undetected atrial

Table 19.1 Advantages and disadvantages of specific ambulatory ECG recording techniques

Selection of ambulatory ECG recording technique			
Recorder type	Advantages	Disadvantages	Duration of use
Holter monitor	1. Continuous ECG Recording 2. No activation required by patient 3. Preferred method for daily symptoms	1. Less useful for infrequent symptoms 2. Continuous monitoring at times uncomfortable/ inconvenient for patients	24–48 h
Noninvasive event monitor	1. Intermittent ECG Recording 2. Transtelephonic downloading of events for immediate assessment 3. Preferred for infrequent symptoms (weekly or monthly) without causing loss of consciousness	1. ECG wires must be attached and activated by patient with each event 2. Less useful for brief symptoms 3. Less useful for arrhythmias that cause loss of consciousness	Weeks – Months
Loop monitor	1. Intermittent ECG Recording 2. Transtelephonic downloading of events for immediate assessment 3. Preferred for infrequent or brief symptoms that may cause loss of consciousness	1. Continuous wearing required 2. Recorder must be activated by patient with each event	Weeks – Months
Implantable loop recorder (ILR)	1. Continuous monitoring with intermittent ECG recording up to 40 min 2. Preferred for rare symptoms which cause loss of conciousness	1. Must be surgically inserted 2. Risk of infection 3. Higher cost than other noninvasive techniques	Up to 3 years

Table 19.2 Indications for AECG to assess symptoms possibly related to rhythm disturbances

A. Indications for AECG to assess symptoms possibly related to rhythm disturbances	
Class I	1. Unexplained syncope, near syncope, or episodic dizziness in whom the cause is not obvious 2. Unexplained recurrent palpitations
Class IIb	1. Episodic shortness of breath, chest pain, or fatigue that is not otherwise explained 2. Neurological events when transient atrial fibrillation of flutter is suspected 3. Syncope, near syncope, episodic dizziness, or palpitations in whom a probable cause other than an arrhythmia has been identified, but in whom symptoms persist despite treatment
Class III	1. Syncope, near syncope, episodic dizziness, or palpitations in whom other causes have been identified 2. Cerebrovascular accidents without other evidence of arrhythmia
B. Indications for AECG for ischemia monitoring	
Class I	None
Class IIa	Patients with suspected variant angina
Class IIb	1. Evaluation of patients with chest pain who cannot exercise 2. Preoperative evaluation for vascular surgery of patients who cannot exercise 3. Patients with known coronary artery disease and atypical chest pain syndrome
Class III	1. Initial evaluation of patients with chest pain who are able to exercise 2. Routine screening of asymptomatic patients

Source: Crawford et al. [1]

Table 19.3 Indications for AECG to assess antiarrhythmic drug and device therapy

A. Indications for AECG to assess antiarrhythmic drug therapy	
Class I	To assess antiarrhythmic drug response in individuals in whom baseline frequency of arrhythmia has been characterized as reproducible and of sufficient frequency to permit analysis
Class IIa	To detect proarrhythmic responses to antiarrhythmic therapy in patients at high risk
Class IIb	1. To assess rate control during atrial fibrillation 2. To document recurrent or asymptomatic nonsustained arrhythmias during therapy in the outpatient setting
B. Indications for AECG to assess pacemaker and ICD function	
Class I	1. Evaluation of frequent symptoms to exclude myopotential inhibition and pacemaker-mediated tachycardia and to assist in the programming of advanced features such as rate responsivity and mode switching 2. Evaluation of suspected component failure or malfunction when device interrogation is not definitive in establishing a diagnosis 3. To assess the response to adjunctive pharmacological therapy in patients receiving frequent ICD therapy
Class IIb	1. Evaluation of immediate postoperative pacemaker function after pacemaker or ICD implantation as an alternative to continuous telemetric monitoring 2. Evaluation of the rate of supraventricular arrhythmias in patients with implantable defibrillators
Class III	1. Assessment of ICD/pacemaker malfunction when device interrogation or other available data are sufficient to establish a cause/diagnosis 2. Routine follow-up in asymptomatic patients

Source: Crawford et al. [1]

fibrillation in patients presenting with cryptogenic stroke. Ambulatory monitoring techniques can also be used to screen patients for asymptomatic premature ventricular contractions and nonsustained ventricular tachycardia for purposes of risk stratification. AECG can provide useful information for risk stratification for sudden cardiac death in selected patients. These include those patients with hypertrophic cardiomyopathy, long QT syndrome, congenital heart disease, arrhythmogenic right ventricular dysplasia, ischemic heart disease, and dilated cardiomyopathies

The method of initial ambulatory ECG monitoring for the symptomatic patient depends largely on the frequency and severity of symptoms. Holter monitoring for 24–48 h is most practical as the initial monitor for patients with daily or near daily symptoms. Holter monitoring is also a reasonable approach to assess rate control in patients with atrial fibrillation and for risk stratification for patients with selected types of cardiovascular disease as noted above. By contrast, noninvasive or invasive loop monitoring has a higher diagnostic yield in patients with less frequent symptoms. Such monitoring is appropriate if symptoms occur weekly or monthly but do not prevent the patient from activating the device. Currently, there are three distinct methods for intermittent ECG recording (Table 19.1).

Contraindications

As a simple, non-invasive technique, there are few absolute contraindications for AECG. However, in patients with previous allergic reactions to the adhesives used in lead attachment, alternative methods should be used, or the patient should be monitored closely for adverse reactions. As a diagnostic test, the ACC/AHA guidelines [2] explicitly discourage the use of AECG for patients with syncope or other symptoms if other causes have been identified. In addition, published guidelines discourage the use of AECG in patients with strokes who are at low risk without other evidence of arrhythmia. These guidelines also do not support the use of AECG for the evaluation of myocardial ischemia, with the exception of suspected variant angina (Table 19.2). Although not contraindicated, AECG also plays a limited role in the assessment of pacemaker and ICD function, and should not be used when data available from device interrogation are sufficient to guide patient management (Table 19.3).

Equipment

The conventional AECG system uses a small, lightweight, battery operated electromagnetic tape recorder connected to bipolar electrodes that is capable of recording in 3 or 12 lead ECG format on a magnetic tape cassette, microcassette, or compact disk. These devices include patient-activated event markers and encoded time markers for simplified data retrieval. Recorded data can be converted to a digital format and analyzed using commercially available software that helps identify

arrhythmias. Devices that allow trans-telephonic downloading are capable of ECG transmission via telephone by converting the ECG data into an audio signal. Upon receipt at a central location, the audio signal is reconstructed into a conventional ECG recording for printing and analysis.

Newer devices now allow for direct recording of the ECG signal in a digital format. This technology avoids potential biases introduced by tape recording as well as problems associated with analog-to-digital conversion before analysis. These recordings allow for extremely accurate reproductions of the ECG signal for more advanced analysis by computer algorithms. Digital recording devices are currently limited by higher costs and smaller storage capacity, although this technology is rapidly advancing.

Techniques of AECG

Correct patient connection to the device is the single most important step in AECG recording. For standard 24-h Holter monitors, five, seven, or ten electrodes are placed in standardized lead positions using adhesive gel after the skin sites are shaved and prepped. From these positions, the operator is able to obtain 3 or 12 lead ECG recordings. The number and arrangement of lead wires is determined by the operator at the time of the recording depending on the number of ECG leads that are desired. The operator can then set the desired duration of time for 3 and 12 lead recording to be obtained by the device during the recording period. Patients are instructed to wear the recorder for 24–48 h, performing their daily activities as normal. During the recording period, patients should avoid any activities that could cause the recorder or the electrodes to become wet. They are also advised to avoid equipment or appliances (such as microwave ovens) that may cause electromagnetic interference. All symptoms, activities, and medications taken should be recorded by pressing the Event button on the recorder and entering the event into either the Digital Diary or the paper diary provided.

In comparison to the traditional 24-h Holter monitor, loop monitors utilize two attached ECG leads that can be worn continuously for several weeks. Patients are instructed to detach the device for bathing. At the onset of symptoms, the device is patient-activated for up to 300 s of recording a single ECG lead. In contrast, events monitors do not require ECG lead attachment at the onset of symptoms. Rather, the recorder itself contains four ECG electrodes that are held directly to the chest wall for recording during an episode. Recorded rhythms for both devices then can be downloaded via telephone to a central location.

Data Interpretation

Following the recording period, the saved ECG can then be analyzed using commercially available software which displays and prints selected ECG rhythm strips. In addition, the software provides trend information including

ST-segments, heart rate (measured R-R interval) and heart rate variability, total ventricular and supraventricular premature beats, and ventricular tachycardia and supraventricular tachycardia beat counts. Accuracy of ECG interpretation varies depending on the amount of background artifact in the recording and with the software system used for analysis. The system is designed to detect all important arrhythmia episodes with high sensitivity, but despite advances in the accuracy of software-based analysis, all recorded rhythms must be overread by an experienced clinician. When used in combination with a detailed diary of patient symptoms, the diagnostic yield of these devices is high. The ability to temporally correlate ECG abnormalities with patient symptoms is the unique strength of this technique.

Complications

As a simple, non-invasive test, there are no significant complications resulting from this technique. However, the risk of misdiagnosis is a potential limitation of ambulatory monitoring. In several large studies, correlation between rhythm abnormality documented using Holter monitoring and symptoms such as syncope was <5 % [3]. If an asymptomatic rhythm abnormality is detected, it may lead to additional unnecessary diagnostic testing.

Conclusions

It is evident that the clinician has multiple techniques of AECG monitoring available as diagnostic tools. The indication for the monitoring as well as the frequency and duration of the symptoms need to be carefully considered in choosing the best monitoring approach. The likelihood of making a diagnosis for patients with intermittent, rare symptoms such as syncope, presyncope or palpitations is increased with extended duration of monitoring. By contrast, when monitoring is being performed to assess the effects of therapy such as rate controlling drugs in atrial fibrillation or risk stratification, Holter monitoring for 24–48 h is sufficient. Holter monitoring is also the appropriate method of AECG monitoring as an initial step in patients with frequent symptoms occurring daily or more frequently. By contrast, noninvasive loop monitoring is preferred for patients with less frequent symptoms. In the absence of a diagnosis despite noninvasive loop monitoring, it is reasonable to move forward with an invasive approach with an ILR. Clinicians should remember that the ILR are most useful for patients with extremely infrequent symptoms. However this invasive approach should generally be reserved for patients in whom noninvasive AECG techniques have failed to yield a diagnosis.

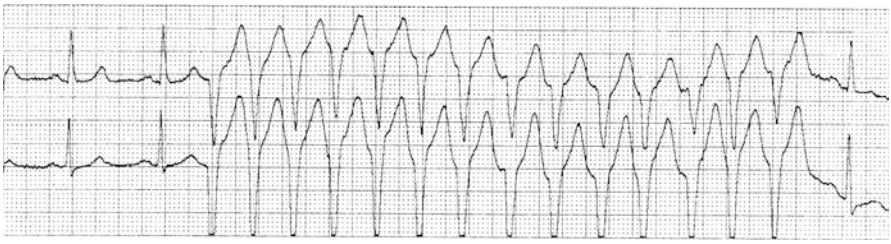

Fig. 19.1 Case #1 (see text for details)

Clinical Vignettes

Case 1

A 60 yo male presents with recurrent palpitations. He has a history of anterior myocardial infarction 2 years previously with moderately reduced left ventricular function (ejection fraction 35 %).

A 24-h Holter monitor is performed which documents an episode of nonsustained monomorphic ventricular tachycardia (VT), corresponding with symptoms of palpitations (Fig. 19.1). The patient undergoes electrophysiology testing which reveals inducible sustained VT, and an Implantable Cardioverter Defibrillator (ICD) is placed.

Case 2

A 65 yo female presents with frequent palpitation, lightheadedness, and two episodes of syncope. She has a history of paroxysmal atrial fibrillation.

A 24-h Holter monitor is performed which reveals an episode of atrial fibrillation terminating with a 9.2 s pause and sinus arrest during sleep (Fig. 19.2). She is treated for sick sinus syndrome with a permanent pacemaker.

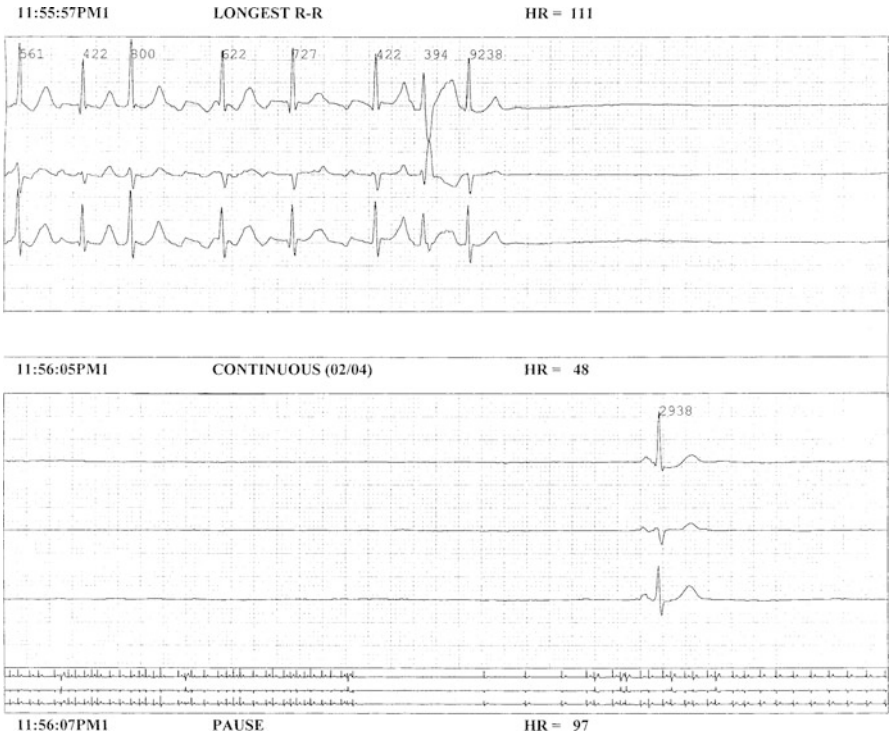

Fig. 19.2 Case #2 (see text for details)

Case 3

A 20 yo male is referred for occasional palpiations. He has no significant past medical or family history, and does not report dizziness, pre-syncope, or syncope.

A Holter monitor is performed which records an episode of sinus rhythm with Mobitz II second-degree AV block (Wenckebach) in the early morning hours during sleep (Fig. 19.3). No other significant arrhythmias were documented despite several episodes of symptoms. No specific therapy was warranted.

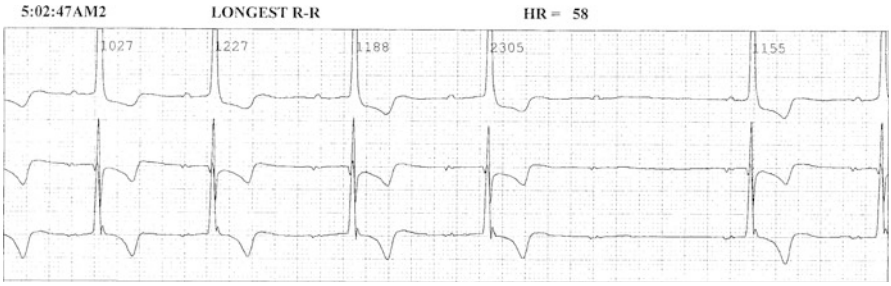

Fig. 19.3 Case #3 (see text for details)

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Chapter 20
Tilt Table Testing

Alexis P. Rodriguez

Introduction

Tilt table testing (TTT) was introduced about two decades ago for the evaluation of patients with unexplained syncope. Initially, it was welcome and spread enthusiastically through different medical specialties, but its use has decreased due to the recognition of several limitations when inappropriately employed. Nonetheless, the generalized consensus still stands that TTT remains an important diagnostic tool in the correct patient population.

Indications

TTT has been used for the evaluation of postural tachycardia syndrome, inappropriate sinus tachycardia, and vasovagal syncope. It is especially useful in the evaluation of recurrent episodes of syncope in the absence of organic heart disease, or in patients with prior cardiomyopathy diagnosis in whom other syncope etiologies have been excluded. Furthermore, TTT is also a practical option to discriminate between convulsive syncope and epilepsy, to establish a diagnosis of pseudosyncope, and lastly to evaluate patients with hypotension that are less likely to respond to permanent cardiac pacing. Additionally the diagnosis of delayed orthostatic hypotension syndrome can be successfully made through TTT after all other diagnostic studies are negative. Nonetheless, it should not be used when the vasovagal syncope diagnosis is certain; or to guide therapy, its response, or lack thereof [1].

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Fig. 20.1 The patient is secured on a padded table with may be placed in a variety of positions, as opposed to position

Contraindications

Though a high volume of TTT are performed on a yearly basis, the ordering clinician should be aware of its contraindications. While considered a safe test, complications still may arise from decreased perfusion to the heart, brain, or other organs. Some of the most important contraindications include a history of severe tachyarrhythimas, electrolyte imbalance, end-stage renal disease, left ventricular outflow tract obstruction, severe cerebral or coronary artery disease, hypotensive shock, recent stroke, and lower extremity fracture.

Equipment

The test is performed generally in the electrophysiology laboratory. A tilt table is required, and should be as comfortable as possible (Fig. 20.1). A blood pressure monitor, ECG machine, and oxygen saturation monitor are also needed. Since one of the possible complications is the development of dangerous tachyarrhythmias, a crash cart with defibrillator should be available. During the testing phase, the room

should remain quiet comfortable by minimizing disruptive noises, or uncomfortable extreme range of temperatures.

Technique

Multiple protocols have been developed varying the angle tilt, its duration, and the concomitant use of pharmacologic agents. The patient is placed supine and vital signs are closely monitored to obtain a personal baseline. It is recommended that if venous cannulation had been performed prior to the test, the monitoring period should be longer. Another important consideration is to avoid invasive intra-arterial blood pressure monitoring during TTT because catheterization may induce in some individuals a vasovagal reaction. The patient is positioned in a head-up position. The recommendation is that the tilt angle be between 60° and 70°; however, steeper angles have been described. Heart rate and blood pressures are recorded every 3–5 min and a symptom diary is maintained. Pharmacologic agents can induce symptoms in patients that have remained asymptomatic. Isoproterenol, a non-specific beta agonist, used as an infusion is commonly employed. The infusion is titrated from 1–3 mcg/min to increase the heart rate up to 25 % above the recorded baseline, and then the head-up tilt phase of the study begins. Another important consideration is that isoproterenol is contraindicated in patients with ischemic heart disease. Nitrates have also been showed to have some use in tilt table testing, intravenous infusion or sublingual nitrates. Nitrates work by inducing venodilation, and, thus, reducing cardiac preload, stroke volume, and output. Yet, it does not hamper increases in heart rate or arterial constriction. Like isoproterenol, nitrates decrease the exam duration but are better-tolerated and easier to use [2].

Data Interpretation

Test interpretation depends on the clinical setting for indication in the first place. In patients without structural heart disease, TTT is determined to be diagnostic for different outcomes. First, for the evaluation of reflex hypotension or bradycardia that may, or not, be accompanied of spontaneous syncope. Secondly, when the patient develops progressive orthostatic hypotension even if there are no associated symptoms. In selected patients being assessed for POTS, TTT may play a diagnostic role, but it is still discretionary to the ordering physician. In patients with structural heart disease, arrhythmias should be excluded before considering a test to be diagnostic. Reproduction of a syncopal event even in the absence of hypotension or bradycardia is in turn suggestive of psychogenic pseudosyncope. The rate of false positives and negatives depends on the patient population; however, these are difficult to estimate given that there is no gold standard testing for comparison.

If the patient has remained asymptomatic during TTT, and there is suspicion for false negative results, it is recommended that the test be repeated using isoproterenol. Though relatively safe for most patients, isoproterenol should be avoided in patients with angina and history of arrhythmia. While most make no discriminations regarding test results when isoproterenol is used, some cardiologists make the distinction that a test is positive only if there is loss of consciousness or postural tone. Nonetheless, the most current guidelines do not include separate diagnostic criteria for TTT with concomitant isoproterenol [2]. Nitrates, like isoproterenol, may increase the rate of false positives. Trials comparing nitroglycerin to isoproterenol have been conducted, thus, showing similar results; however, sublingual nitroglyerine was simpler to administer, much better tolerated, and safer than low-dose isoproterenol [3, 4].

Complications

As previously stated, TTT is rather safe, and severe complications are rare; however, as with any other medical procedure, there are still some intrinsic risks that both patient and practitioner should be aware. Potential complications include, prolonged hypotension, tachyarrhythmias, syncope, and rarely asystole. Most of these complications resolve when the table is turned back to the horizontal position. Nonetheless, precautionary measures should be taken and readily available including cardiopulmonary resuscitation equipment.

Clinical Vignettes

Case 1

Mrs. Jones is a 40 year-old lady that comes to the office for evaluation of syncope. She has a history of hypertension, hypothyroidism, dyslipidemia, and obesity. She takes synthroid 125 mcg daily, and her primary care physician discontinued hydrochlorothiazide over a year ago as her blood pressure seemed better controlled. She experienced her first syncopal event about 3 months ago while getting up from a chair, and then another one last week after standing for some time. She recalled that the same thing used to happen in her "earlier years." Before both events, she felt her vision darkened and the room spin for some seconds. Both events were witnessed, and the loss of consciousness was transitory and resolved by itself. There was no tongue biting or sphincter incontinence. She had no post-ictal period. However, per her son, there was some lower extremity jerking movements. She has undergone extensive diagnostic studies including brain images; thus far, no clear etiology given. She undergoes TTT with hypotension and reproduction of symptoms.

Mrs. Jones has had two syncopal episodes that have prompted a medical evaluation. After extensive and thorough evaluation, there is no clear etiology. However,

no pertinent positive findings have been noted. While it can be argued, that given the history, this is very likely consistent with vasovagal syncope, there is the confounding factor of lower extremity jerking, which can also be seen in syncope of cardiac nature. The TTT is considered to be positive given her vital signs response and reproduction of symptoms. Mrs. Jones should be advised regarding hydration, prolonged standing, or sudden changes in position. The patient should also be educated on abortive procedures if she experiences an aura.

Case 2

A 28 year old woman is referred for the evaluation of recurrent fainting episodes. These started about 2 years ago, and have consistently recurred. She has no medical history, other than generalized anxiety disorder, and takes no medications or over the counter supplies. The episodes occur without an aura, or clear precipitating event. These last between 5 and 20 min, and the patient just experiences some residual weakness and left lower extremity weakness. She has undergone extensive neurologic evaluation (including MRI and EEG) without a definitive diagnosis. Furthermore, EKG and echocardiography do not show any abnormalities. At the primary care physician's office her blood pressure was borderline low, but otherwise her vitals were normal. She undergoes TTT, and her vitals remain unchanged but the patient experiences another episode. A psychiatry consultation is placed, and the diagnosis is changed to psychogenic seizures and possibly conversion disorder. With the patient and her family understanding the diagnosis, psychotherapy was started and follow up appointments were provided.

This patient comes with complaints of recurrent syncope without a clear explanation. There is always concern for seizures or syncope of neuro-cardiogenic nature. These seem to have been ruled out. The possibility of vasovagal syncope has to be considered. Her blood pressure was marginally low; however, this is a non-specific finding especially in young healthy individuals. TTTs that reproduce the loss of consciousness without changes in vital signs are suspicious for a psychogenic etiology. The patient and family should be engaged in the therapy, which should remain empathic and consistent throughout. It is crucial to recognize that most of these events are involuntary, legitimate, and disabling to the patient. She should enroll in behavioral and group psychotherapy, and considered for antidepressant or antipsychotic pharmacotherapy.

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Chapter 21
Electrophysiologic Testing

Jonathan Weinstock and Christopher Clyne

There are a wide variety of clinical scenarios in which electrophysiology studies (EPS) may be useful, as a way to diagnose symptoms such as palpitations or syncope, to define mechanisms and possibly treat a documented arrhythmia, or to aid in determining a patient's risk for sudden cardiac death from ventricular arrhythmias. Furthermore, EPS may be used to assess known or suspected conduction abnormalities. Most EPS are performed via electrode catheters in the heart, but some are performed with non-invasive programmed stimulation (NIPS) that refers to a limited electrophysiology study performed via an implanted cardiac device, either a pacemaker or a defibrillator.

Indications

Invasive EPS can be of use in patients with suspected or known sinus node dysfunction. EPS is helpful in determining a causal relationship between suspected sinus node dysfunction and symptoms in cases where a non-invasive evaluation has failed to establish the link. Indications for EPS in patients with known or suspected AV block, include those in whom His-Purkinje block is suspected as the cause of symptoms, but has not been definitively established, including those with pre-existing conduction abnormalities such as those in whom the surface electrocardiogram (ECG) documents a bundle branch block.

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EPS are indicated in patients with recurrent supraventricular tachycardia (narrow QRS complex <120 ms), to better define the mechanism of the arrhythmia and for selection of the appropriate therapy, either medical or ablation. Wide complex tachycardias (wide QRS >120 ms) may be a result of either supraventricular arrhythmias with intraventricular conduction delay (aberration), pre-excitation in the Wolff-Parkinson-White syndrome, or ventricular tachycardia. When the mechanism of documented arrhythmias is not clear on a surface ECG, EPS are indicated to define the mechanism and guide therapy. Non-invasive programmed stimulation (via an ICD) is indicated in patients who have ventricular arrhythmias, in whom prescription of new antiarrhythmic medications may alter the characteristics of the tachycardia, which affects the programming of their ICD.

Indications for EPS in patients with Wolff-Parkinson-White syndrome (WPW) include patients in whom ablation of an accessory pathway is planned, and patients with WPW manifest on a surface ECG who suffer a cardiac arrest or syncope. Asymptomatic patients with WPW who have a family history of sudden cardiac death, or who engage in high risk occupations, may require EPS, for risk stratification, and to determine the best therapy if required, including pharmacologic or ablation therapies.

In patients with left ventricular dysfunction, non-sustained ventricular tachycardia can be a risk factor for sudden cardiac death. EPS with ventricular stimulation is indicated in patients with non-sustained ventricular tachycardia, coronary artery disease, and left ventricular dysfunction for risk stratification, where if inducible for ventricular arrhythmias, patients may benefit from implantation of a cardiac defibrillator. In patients with non-ischemic cardiomyopathy, the results of ventricular stimulation are not predictive of risk. Patients with highly symptomatic, drug resistant, uniform premature ventricular contractions; or non-sustained ventricular tachycardia (with or without structural heart disease) may undergo and EPS to localize the arrhythmia, and allow for ablation.

EPS are indicated in patients with syncope and structural heart disease in whom the cause of syncope is unknown after routine evaluation. Additionally, patients without structural heart disease who have recurrent unexplained syncope despite an appropriate non-invasive workup may require EPS to assist in the diagnosis. EPS are indicated in patients with recurrent palpitations in whom repeated efforts to obtain electrocardiographic recordings have failed, or in patients in whom palpitations preceded a syncopal event.

Contraindications

As with most intravascular cardiac procedures, EPS are contraindicated in the presence of significant coaguloapathies or known obstruction to venous access. EPS should not be performed in the setting of hemodynamic instability, acute exacerbations of heart failure, systemic infection, and respiratory distress. Additionally, EPS is contraindicated in patients with left main coronary disease, a large burden of cardiac ischemia, severe aortic stenosis, acute myocardial infarction, or unstable angina.

Equipment

Equipment required to perform EPS, is similar to other cardiac catheterization equipment and includes a fluoroscopic unit, a patient table suitable for radiography, a physiologic recorder and display for hemodynamic, surface electrocardiography and intracardiac recordings, and equipment for intravascular access. Equipment for emergencies such as an external defibrillator, tools for airway support, and emergency medications should be easily available in the room in which the procedure is performed.

Unique to EPS are a programmable stimulator, a junction box, and electrode catheters. The stimulator is a device that is capable of delivering accurately timed (within 1 ms) stimuli via intracardiac catheters triggered either by previously paced beats or intrinsic beats. Multiple stimuli can be delivered with complex timing sequences. The junction box acts as a common location for catheters to connect to the recording and pacing equipment. Specialized catheters are used which have a variable number of electrode pairs on their ends, to both record intracardiac electrical activity and deliver pacing stimuli to the heart. Some electrophysiology laboratories are equipped with additional equipment such as 3-D mapping systems that assist in the diagnosis and localization of arrhythmias, and specialized ablation catheters and generators (radiofrequency and cryo-thermal energies) for delivery of catheter directed energy that destroys the arrhythmia focus.

Technique

The patient is brought to the electrophysiology laboratory in the fasting state and the sites of venous access are sterilized with either betadine or chlorhexadine, after which the patient is draped. General anesthesia is rarely used for diagnostic EPS, as the vast majority of procedures can be achieved by conscious sedation with the use of benzodiazepines and other drugs. General anesthesia may be employed for longer procedures such as atrial fibrillation or ventricular tachycardia (VT) ablations. The sites of access are almost always the femoral veins, with only the rare need for arterial access. Occasionally access is gained from the upper extremity, the subclavian, or internal jugular veins, either because of a contraindication to the femoral approach, or for ease of placement of a particular catheter, usually the coronary sinus, which sometimes can be difficult from an inferior approach.

Venous access is gained via the Seldinger technique, and a series of sheaths are placed intravenously. Through these sheaths a number of multipolar electrode catheters are positioned under fluoroscopy in standard locations in the heart. Between 2 and 4 catheters can be used for an EPS, depending on the clinical scenario. Standard catheter positions include the high lateral right atrium, the His bundle position, and right ventricular apex (Fig. 21.1). A complete ventricular stimulation protocol also includes the repositioning of the right ventricular catheter in the right ventricular

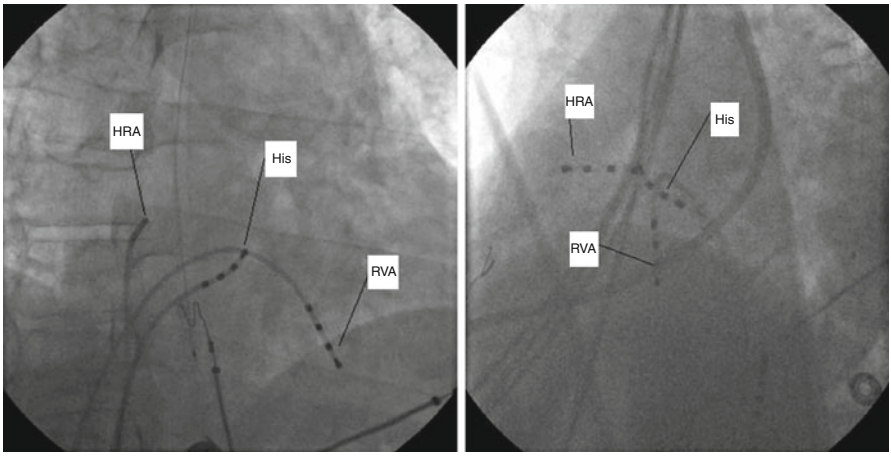

Fig. 21.1 AP and Lateral views of cardiac silhouette with three diagnostic (quadripolar) catheters placed in the high right atrium (*HRA*), across the tricuspid annulus for His bundle recording (*His*), and in the right ventricular apex (*RVA*)

outflow tract- below the pulmonic valve. If the EPS is designed to specifically diagnose or induce supraventricular arrhythmias (SVT), an additional multipolar catheter is usually positioned within the coronary sinus from the right atrium. If needed, access to the left atrium and ventricle, may be achieved via a transseptal puncture of the intra-atrial septum, or retrograde across the aortic valve via the femoral artery and aorta.

A basic EPS consists of a standard protocol that assesses baseline characteristics of the conduction system followed by attempted induction of arrhythmias. EPS begins with the measurement of baseline conduction intervals beginning with those on the surface electrocardiogram such as PR interval, and QRS width, and includes the intra-cardiac intervals measuring the time for conduction from the atrium to the His bundle deflection (AH interval), and from the His bundle deflection to the ventricular activation deflection (HV interval) (Fig. 21.2).

Pacing maneuvers are employed to assess sinoatrial (SA) node function and conduction properties from the atrium to ventricle (AV conduction), from the ventricle back to the atrium (VA conduction), and of the atrio-ventricular node (AVN)-including the rate at which the AVN displays both antegrade and retrograde Wenkebach and 2:1 conduction block. Introduction of premature atrial stimuli is performed in a standard fashion to further define the arrhythmogenic substrate (dual AVN pathways; accessory pathways), and to expose various forms of SVT's (AV nodal reentry, AV reentry, atrial arrhythmias). These pacing maneuvers also help to define the refractoriness of the AV node, and to characterize the antegrade conduction properties of an existing accessory pathway. Similar maneuvers are performed from

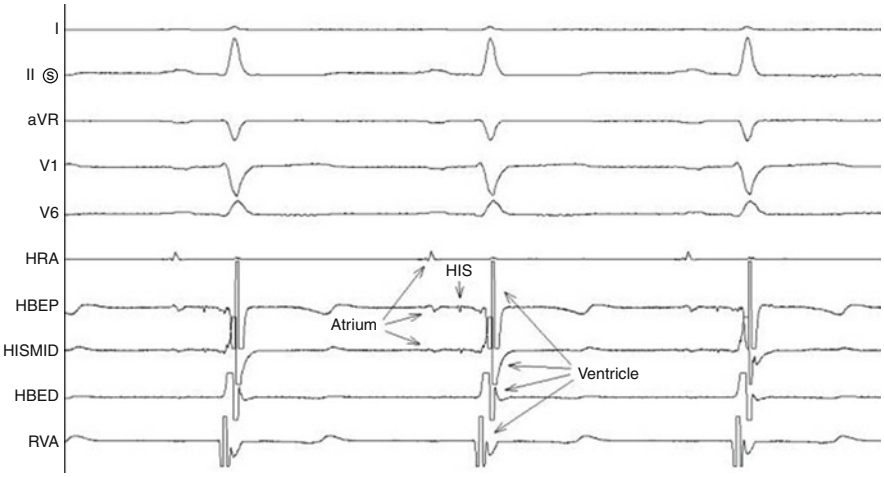

Fig. 21.2 Recording of sinus rhythm during an electrophysiology study. The top six tracing are from the surface electrocardiogram, the next five lines are intra-cardiac recordings from the high right atrium (*HRA*), proximal His bundle (*HBEP*), mid His bundle (*HISMID*), distal His bundle (*HBED*) and right ventricular apex (*RVA*). The recording speed is 50 mm/s. The deflections on the individual catheters are labeled as atrium, His bundle, and ventricle, corresponding to sensed depolarization of each structure

the ventricle (s) to characterize ventricular conduction and detect ventricular arrhythmias (VT, VF).

Various pacing maneuvers are performed in a variety of locations in an attempt to induce supraventricular or ventricular tachycardia. Extra-stimuli are delivered in increasing numbers [1–3] and prematurity after a drive train of eight beats from multiple sites (RA, RVA, RVOT, +/−CS/LA) in an attempt to induce an arrhythmia. The administration of drugs such as epinephrine, isoproterenol or atropine is often added to standard induction protocols to increase the chance of induction. Optimal therapy (drug, ablation, or device) can be planned if an arrhythmia is reproduced. Hemostasis is achieved with manual pressure at the end of the procedure after the catheters and sheaths are removed.

Data Interpretation

Abnormal sinus node function indicated by a long sinus node recovery time (the interval following atrial pacing after which the sinus node fires) in combination with unexplained syncope is an indication for a permanent pacemaker.

A prolonged HV interval (≥100 ms), or easily induced block in the His-Purkinje system (infra-Hisian) is a relative indication for a permanent pacemaker as it predicts a high likelihood of progressing to high degree AV block.

The presence of two AV nodal pathways with atrial pacing maneuvers suggests AV nodal reentry tachycardia as the etiology of a supraventricular arrhythmia in symptomatic patients.

Induction of monomorphic VT in a patient with unexplained syncope identifies a cause for the syncope, and an indication for an ICD.

The reproducible induction of a supraventricular tachycardia in the electrophysiology laboratory allows for a variety of pacing maneuvers to be performed during the tachycardia. These maneuvers in combination with the initiation and termination characteristics of the arrhythmia allow for an exact diagnosis of the arrhythmia by careful analysis of the intracardiac recordings. Most supraventricular tachycardias are amenable to relatively safe and effective ablation procedures, which can be performed in the same session [4]. Atrial flutter, AV nodal reentry tachycardia, atrioventricular reciprocating tachycardia (WPW), and atrial tachycardia are examples of supraventricular tachycardias that can be cured with ablation.

Ventricular tachycardias may be characterized and identified by their location, morphology, rate and induction characteristics. Sustained monomorphic ventricular tachycardia is a more specific finding than polymorphic ventricular tachycardia or ventricular fibrillation. Specificity is greatest with induction at the right ventricular apex with low number of slower extrastimuli. The specificity decreases as the number and rapidity of extrastimuli increase. Localization of the tachycardia via 3-D mapping techniques allows for the ablation of stable VT's in appropriate ablation candidates.

Complications

Bleeding and hematoma formation either superficially or in deep tissue (retroperitoneum) is a potential complication of EPS. Venous thromboembolism (DVT/PE) occurs in approximately 0.05 % of EPS procedures. The risk of arterial thromboembolism (peripheral arterial embolus, CVA) increases when catheters are placed in the left atrium or left ventricle making anticoagulation necessary during the procedure. Cardiac tamponade as a result of cardiac perforation by electrode catheters occurs in approximately 0.08 % of studies, but is higher if ablation is performed. The risk of death from EPS is rare despite the routine induction of life-threatening arrhythmias, as the response to such events in such a controlled setting results in a rapid effective response.

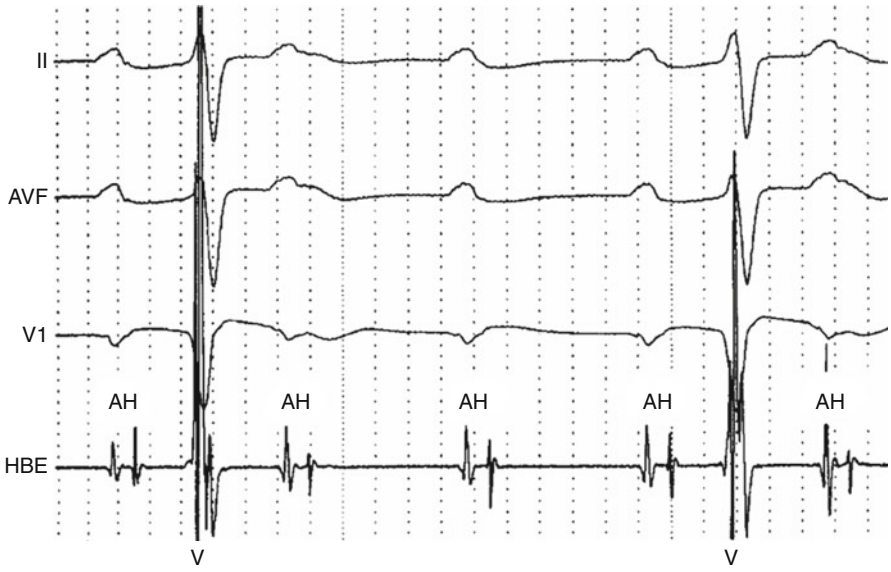

Fig. 21.3 Electrophysiology study recording of a patients with syncope and type 2nd second-degree heart block. The first three tracings are surface leads, HBE is the electrogram recorded at the His bundle. An A (atrial) deflection is followed on each occasion by an H (His) deflection. Only the first and fourth atrial impulse conduct to the ventricle signified by V. The remainder of the atrial impulses block at the infra-Hisian level

Clinical Vignettes

Case #1

A 76-year-old man presented with recurrent syncope, and a left bundle branch block on ECG. EPS revealed block below the bundle of His (Fig. 21.3). A permanent pacemaker was implanted, and his syncope did not recur.

Case #2

A 62-year-old man with a remote myocardial infarction, reduced left ventricular ejection fraction (40%), presented with recurrent syncope. Ventricular tachycardia was induced during an electrophysiology study (Fig. 21.4). An ICD was implanted and he subsequently received appropriate shocks for ventricular arrhythmias.

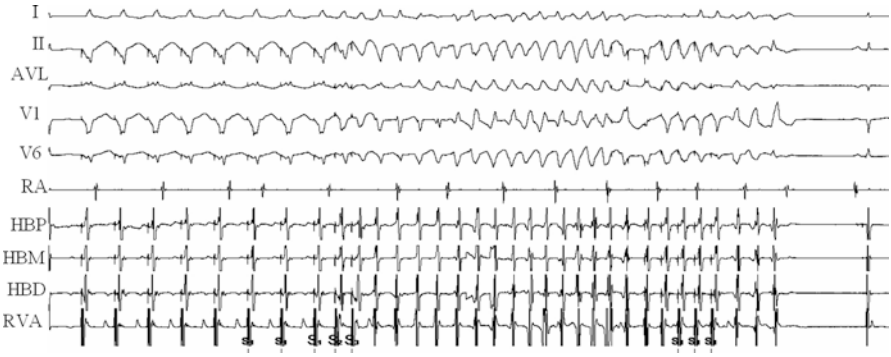

Fig. 21.4 Tracing from an electrophysiology study during induction of ventricular tachycardia. The first five recordings are surface ECG, followed by *RA* (right atrium), *HBP* (His bundle proximal), *HBM* (His bundle mid), *HBD* (His bundle distal) and *RVA* (RV apex). The first eight QRS complexes result from ventricular pacing, followed by two premature stimuli, which induced ventricular tachycardia. Rapid ventricular pacing terminates the tachycardia

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Chapter 22
Temporary Transvenous Pacing

Alawi A. Alsheikh-Ali and Mark S. Link

Indications

Temporary cardiac pacing is generally indicated for the acute management of serious and often symptomatic bradyarrhythmias, that are refractory to medical therapy [1]. Several approaches to temporary pacing are available, including transvensous, transcutaneous, epicardial, and transesophageal. Compared to the other modalities, the transvenous approach is the most stable and readily available option, with the unique ability for selective atrial or ventricular pacing. Conversely, this approach is associated with a variety of complications, and its safe and effective use requires considerable knowledge and technical skill.

Acute myocardial infarction (AMI) is associated with several conduction disturbances, some of which may necessitate temporary transvenous pacing [1]. Generally, temporary pacing should be considered in any patient with AMI and a bradyarrhythmia associated with symptoms or hemodynamic compromise, and those asymptomatic with anterior AMI and alternating bundle branch block, Mobitz II or higher atrioventricular (AV) block. Indications for temporary transvenous pacing in AMI are based on the status of AV nodal and intraventricular conduction, as outlined in Table 22.1. The most ominous sign requiring temporary transvenous pacing in AMI is alternating left and right bundle branch block, which constitutes a Class I indication regardless of the status of AV nodal conduction. Likewise, temporary transvenous pacing in AMI is indicated when Mobitz II second-degree AV block is present, regardless of the status of intraventricular conduction. Other indications for temporary transvenous pacing in AMI are shown in Table 22.1. In general, if the indications for temporary pacing persist for 5–7 days after an AMI, a permanent pacemaker should be considered.

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Table 22.1 Recommendations for temporary transvenous pacing in acute ST-elevation myocardial infarction

	Normal AV conduction	First-degree block	Mobitz I second-degree block	Mobitz II second-degree block
Normal intraventricular conduction	III	III	III	IIa
Old or new fascicular block	III	III	III	IIa
Old bundle branch block	III	IIb	IIb	IIa
New bundle branch block	IIb	IIa	IIa	I
Fascicular block + RBBB	IIb	IIa	IIa	I
Alternating RBBB + LBBB	I	I	I	I

In the absence of an AMI, temporary transvenous pacing should be considered in any patient presenting with acute symptomatic bradyarrhythmia refractory to medical therapy until the offending cause is withdrawn (e.g., beta-blocker, calcium channel blocker, digoxin) and appropriate evaluation for structural or ischemic heart disease and the need for permanent pacing is completed. Other clinical situations where temporary transvenous pacing should be considered include advanced AV block associated with Lyme carditis. Given the reversible nature of bradyarrhthmias in Lyme disease, temporary rather than permanent pacing should be considered if needed. Temporary transvenous pacing is also used after the removal of an infected permanent pacemaker in patients who are deemed pacemaker dependent. A temporary pacermaker is placed until the infection is treated with intravenous antibiotics, after which it is replaced with a new permanent pacer. Similarly, temporary transvenous pacing may be indicated in patients with acute endocarditis (especially with aortic valve involvement) who show signs of conduction disturbance (advanced AV block or new bundle branch block). In addition, prophylactic transvenous pacing should be considered during right heart catheterization or right ventricular endomyocardial biopsy in patients with existing left bundle branch block, given the associated risk of traumatic right bundle branch block during the procedure leading to completer heart block.

Contraindications

The only absolute contraindication to temporary transvenous pacing is refusal by a competent patient. Relative contraindications include a bleeding diathesis that cannot be corrected for safe placement of a temporary transvenous pacer. A decision regarding temporary transvenous pacing depends on the specific clinical situation including the nature of the underlying arrhythmia and availability of other temporary pacing modalities (e.g., transcutaneous or transesophageal). The presence of a mechanical tricuspid valve also precludes the safe placement of a right ventricular temporary pacer although in these situations left ventricular pacing via the coronary sinus may be considered.

Equipment

Temporary transvenous pacing is achieved through intravenously placed catheter electrodes (leads) that are in direct contact with the endocardium. Pacing leads are connected to an external generator providing electrical current pulses to stimulate the myocardium. Pacing leads are most commonly bipolar in configuration in which both the cathode (negative pole) and anode (positive pole) are intracardiac near the tip of the lead. Unipolar configuration can also be used, in which one pole, typically the anode, is extracardia. Pacing leads are either flexible with an inflatable balloon near the tip to direct flow, or semi-rigid without a flow-directing balloon. Semirigid catheters are easier to manipulate and can have preformed distal preformed curvatures for easier manipulation and positioning. Once positioned, the lead is connected to an external generator through which pacing rate and mode, sensitivity, and current output can be adjusted. Alternatively, a permanent screw-in pacing lead can be introduced and then attached to a permanent pacing generator that is securely taped outside the body. This temporary arrangement provides the most lead stability, and allows for prolonged pacing and safe patient ambulation. For any patient in which temporary pacing may be needed for some time (i.e., while treating an infected pacemaker) a permanent screw in lead should be strongly considered. This arrangement is also preferable for atrial pacing.

Technique

As with any procedure involving transvenous insertion of a foreign body, standard sterile techniques should be followed. An external defibrillator with pacing capabilities should be present in the room during lead insertion or manipulation. The right internal jugular vein provides the most rapid and direct route for proper transvenous pacing lead positioning. Subclavian venous access can be used, but carries the added risk of a pneumothorax and injury to the subclavian artery, and is typically saved for a future permanent pacemaker should the patient need one. Femoral vein access can also be used, but carries the added risk of venous thrombosis and a potentially higher infection rate. For positioning in the right atrium, a J-curve configuration is typically used, and the lead is typically advanced to the level of the tricuspid valve, and then withdrawn back gently until it hooks on the right atrial appendage. For right ventricular positioning, the lead is advanced through the tricuspid valve either directly with the tip first, or after formation of a loop in the right atrium under fluoroscopy, which is then advanced through. Once in the right ventricle, gentle advancement and torque is required to reach the apex (counter-clockwise torque if coming in from the superior vena cava, or clockwise if from the inferior vena cava). Once the lead is positioned, appropriate sensitivity and output are confirmed (see below), then the lead is sutured to the skin, and covered with sterile dressing.

Ideally, lead advancement is performed under fluoroscopic guidance to ensure appropriate positioning and minimize risk of cardiac perforation. However, electrocardiographic guidance can be used, whereby the lead is connected to an ECG while being advanced. A large ventricular electrogram indicates presence in the ventricle, while development of ST segment elevation indicates contact with ventricular endocardium. Pacing leads can also be advanced under echocardiographic guidance utilizing the apical or subxiphoid windows for best visualization of the right atrium and ventricle. Under emergency conditions, a pacing lead can be advanced blindly while connected to a generator set to highest output until ventricular capture (paced QRS) is seen. Electrocardiographically, a paced QRS originating from the right ventricular apex should have a left bundle branch block morphology with superior axis. A right bundle branch morphology most commonly indicates pacing from the coronary sinus or left ventricle (i.e., perforation into the left side). Regardless of the guidance modality used, a chest x-ray should be obtained in all patients after a temporary transvenous pacer to ensure appropriate positioning.

Data Interpretation

The term "sensitivity" as used for cardiac pacing relates to the amplitude (often in mV) of the P wave or R wave as seen by the intracardiac electrode in the atrium or ventricle respectively. Sensing threshold (the amplitude above which intrinsic activity is not detected) can be determined by setting the pacemaker to a rate lower than the intrinsic rate, and then lowering the sensitivity (increasing the amplitude on the mV scale) until pacing occurs. Pacing occurs at the sensing threshold because the pacemaker does not "see" the intrinsic beat. Sensitivity is then set at 25–50% the sensing threshold. High amplitude is desired (>1 mV for P wave, and >5 mV for R wave), to allow for a comfortable sensitivity safety margin at which the pacemaker can reliably sense intrinsic activity without running the risk of sensing low amplitude "noise" (i.e., oversensing). Pacing (output) threshold can be determined by setting the pacemaker to a rate higher than the intrinsic rate at low output, and then increasing the output current gradually until myocardial capture (pacing spike followed by a QRS complex) occurs. Optimal pacing threshold is less than 1 mA. Output is typically set at 3–5 times the pacing threshold to allow for any temporal changes in pacing threshold. Both sensing and pacing thresholds should be checked daily and sensitivity and output changed accordingly.

Complications

Complications from temporary transvenous pacing are related to obtaining and maintaining venous access, intracardiac catheter manipulation and retaining an intravascular foreign body [2]. In addition, these leads can perforate the myocardium at

any time after insertion. Risks specific to venous access include bleeding, vascular arterial injury, pneumothorax (with subclavian or internal jugular access), air embolism, cardiac perforation including tamponade, pericarditis, and venous thrombosis/thrombophlebitis (more common with femoral vein approach). Intracardiac catheter manipulation carries the risk of inducing atrial or ventricular tachyarrhythmias. While bacteremia can be demonstrated in many patients with temporary transvenous pacers, clinical infection (including sepsis) is much less common occurring in less than 5 % of patients.

Clinical Vignettes

Case 1

A 50 year old woman with diabetes mellitus, hypertension was noted to be bradycardic with a heart rate of 40 beats per minute during a routine colonoscopy. An electrocardiogram demonstrated complete heart block. She reported an episode of syncope 1 week prior. Given her risk factor profile, work up for coronary disease and structural heart disease was ordered.

While awaiting the ordered workup and given her recent syncope, a temporary transvenous pacer with a screw in lead was placed through a right internal jugular venous approach (Fig. 22.1). A dipyridamole myocardial perfusion scan was normal, and a transthoracic echocardiogram revealed no structural heart disease with a left ventricular ejection fraction of 60 %. A new left sided permanent dual chamber pacemaker system was placed through a left subclavian venous approach (Fig. 22.2a, b) and the temporary pacer was removed.

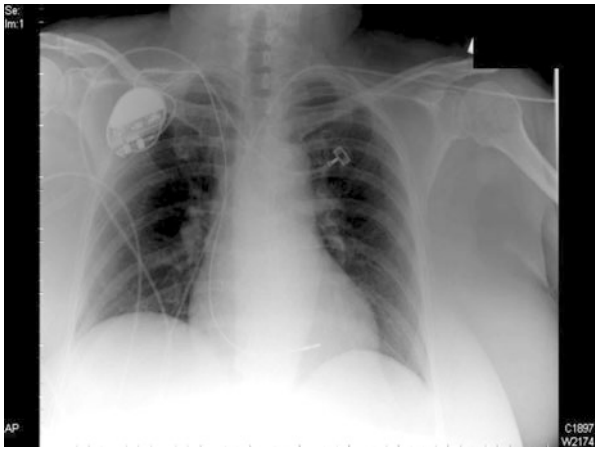

Fig. 22.1 Temporary transvenous screw-in pacing lead is seen placed through right internal jugular vein. The generator (outside the body) is seen next to the right shoulder

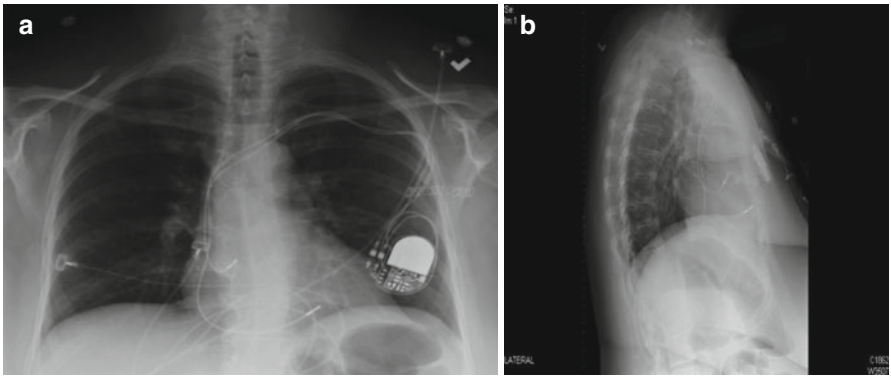

Fig. 22.2 (**a, b**) PA (2A) and lateral (2B) chest radiographs. The temporary pacer has been removed and a new permanent dual chamber pacemaker through the left subclavian vein is in place. Note the anterior orientation of both pacing leads indicating appropriate positioning. A posterior orientation of the ventricular lead would indicate placement in the coronary sinus

Case 2

An 84 year old female with hypertension and dyslipidemia presented with acute pulmonary edema and respiratory distress requiring intubation. Her electrocardiogram showed anterior Q waves in leads V1–V5. A transthoracic echocardiogram showed a left ventricular ejection fraction of 30 %. The patient was noted to have intermittent episodes of complete heart block with a wide QRS complex escape rhythm around 30 beats per minute.

A temporary non-screw in pacing lead was placed urgently through a left subclavian approach (Fig. 22.3). Because of recurrent fevers, and in anticipation of a prolonged hospitalization, a new temporary screw-in lead connected to an external generator was placed through the right internal jugular vein, and the old non-screw in lead removed (Fig. 22.4). Once her infection was treated, a permanent pacemaker was placed and the temporary one removed.

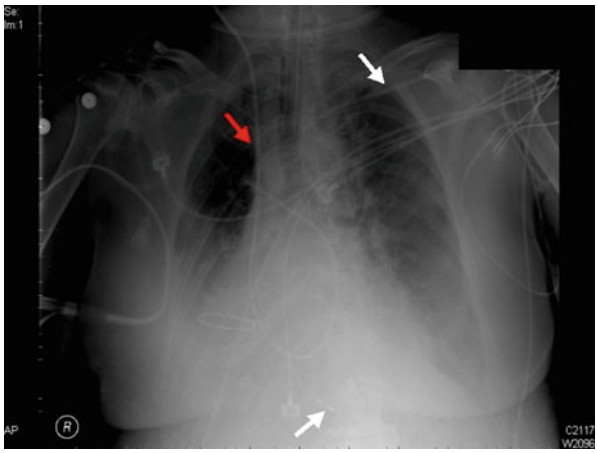

Fig. 22.3 Temporary transvenous non-screw-in pacing lead is seen placed through the left subclavian vein (*white arrow*). A pulmonary artery catheter is also seen placed through the right internal jugular vein (*red arrow*)

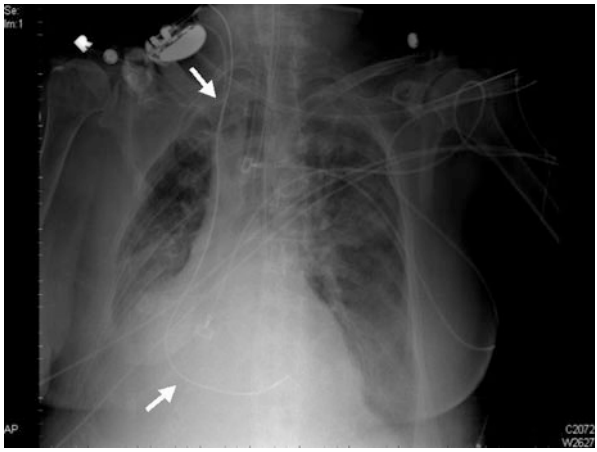

Fig. 22.4 The temporary non-screw in pacer has been removed and a new screw-in lead is seen (*white arrows*) placed through the right internal jugular vein and attached to an external generator

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Chapter 23
Cardiac Pacemakers

Constancia F.C. Macatangay

Currently, three approaches to permanent cardiac pacing are in common use. Single-chamber pacemaker is a device wherein one pacing lead is implanted in either the right atrium or right ventricle. Dual-chamber pacemaker has two pacing leads, one in the right ventricle and one in the right atrium, this is the most commonly used type of pacemaker. Biventricular pacemaker or cardiac resynchronization therapy (CRT) is a device wherein in addition to single- or dual-chamber right heart pacing leads, a third lead is advanced to the coronary sinus for left ventricular epicardial pacing.

Indications

The decision to implant a permanent pacemaker is based on the association of symptoms with a bradyarrhythmia, the location of the conduction abnormality, and the absence of a reversible cause.

A careful history taking and documentation of cardiac rhythm, with either an electrocardiogram or ambulatory monitoring, should be done. Symptoms include dizziness, lightheadedness, syncope, fatigue, and poor exercise tolerance. The direct correlation between symptoms and bradyarrhythmia will increase the likelihood that the pacemaker therapy would result in clinical improvement.

The most common indications for permanent pacemaker implantation are sinus node dysfunction (SND) and high-grade or symptomatic atrioventricular (AV) block. SND refers to abnormalities in sinus node and atrial impulse formation and propagation. It is primarily a disease of the elderly and is thought to be due to senescence of the sinus node and atrial muscle. SND encompasses a wide array of

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abnormalities which include: persistent sinus bradycardia and chronotropic incompetence without identifiable causes, paroxysmal or persistent sinus arrest with replacement by subsidiary escape rhythms in the atrium, AV junction, or ventricular myocardium, and "tachy-brady syndrome". There is no evidence that cardiac pacing prolongs survival in patients with sinus node dysfunction.

Type II second-degree AV block is characterized by fixed PR intervals before and after blocked beats and is usually associated with a wide QRS complex. It is usually infranodal (either intra- or infra-His), especially when the QRS is wide, and typically indicates diffuse conduction system disease. Thus, this type of block constitutes an indication for pacing even in the absence of symptoms. Symptoms are frequent, prognosis is compromised, and progression to third-degree AV block is common and sudden. Third-degree AV block (complete heart block) is defined as absence of AV conduction.

Bifascicular block refers to ECG evidence of impaired conduction below the AV node in the right and left bundles. Please refer to Tables 23.1, 23.2, and 23.3 for a full listing of all the indications for pacemaker pacing in SND, AV block, and chronic bifascicular block.

Pacemaker may also be indicated in neurocardiogenic syncope in which there is a severe or persistent component of bradycardia and more conservative therapeutic attempts have failed. There are other special circumstances which require permanent cardiac pacing: after the acute phase of myocardial infarction, after cardiac transplantation, in sleep apnea syndrome, infiltrative disorders, and neuromuscular disorders [1].

Contraindications

Once it has been established that the bradycardia or a conduction disorder warrants permanent pacing, there are a few contraindications for the actual permanent pacemaker insertion. These include local infection at implantation site and/or active systemic infection with bacteremia.

In general, pacemakers are not indicated for asymptomatic patients. Symptoms due to sinus node dysfunction have to occur during the documented episodes of bra-

Table 23.1 Indications for permanent pacing in sinus node dysfunction [1, 2]

Indication	Strength of indication
Sinus node dysfunction with documented symptomatic bradycardia, including frequent sinus pauses that produce symptoms	Class I
Symptomatic chronotropic incompetence	Class I
Symptomatic sinus bradycardia that results from required drug therapy for medical conditions	Class I
Sinus node dysfunction with heart rate less than 40 bpm when a clear association between significant symptoms consistent with bradycardia and the actual presence of bradycardia has not been documented	Class IIa
Syncope of unexplained origin when clinically significant abnormalities of sinus node function are discovered or proved in electrophysiological studies	Class IIa
Minimally symptomatic patients with chronic heart rate less than 40 bpm while awake.	Class IIb

Table 23.2 Indications for permanent pacing in acquired atrioventricular block in adults [1]

Indication	Strength of indication
3rd degree and advanced 2nd degree AV block at any anatomic level associated with bradycardia with symptoms (including heart failure) or ventricular arrhythmia presumed to be due to AV block	Class I
3rd degree and advanced 2nd degree AV block at any anatomic level associated with arrhythmias and other medical conditions that require drug therapy that results in symptomatic bradycardia	Class I
3rd degree and advanced 2nd degree AV block at any anatomic level in awake, symptom-free patients in sinus rhythm, with documented periods of asystole greater than or equal to 3.0 s, or any escape rate <40 bpm, or with an escape rhythm that is below AV node	Class I
3rd degree and advanced 2nd degree AV block at any anatomic level in awake, symptom-free patients with atrial fibrillation and bradycardia with one or more pauses of at least 5 s or longer	Class I
3rd degree and advanced 2nd degree AV block at any anatomic level associated with postoperative AV block that is not expected to resolve after cardiac surgery	Class I
3rd degree and advanced 2nd degree AV block at any anatomic level after catheter ablation of the AV junction	Class I
3rd degree and advanced 2nd degree AV block at any anatomic level associated with neuromuscular diseases with AV block	Class I
2nd degree AV block with associated symptomatic bradycardia regardless of type or site of block	Class I
Asymptomatic persistent 3rd degree AV block at any anatomic site with average awake ventricular rates of 40 bpm or faster if cardiomegaly or LV dysfunction is present or if site of block is below the AV node	Class I
2nd or 3rd degree AV block during exercise in the absence of myocardial ischemia	Class I
Persistent 3rd degree AV block with an escape rate greater than 40 bpm in asymptomatic adult patients without cardiomegaly	Class IIa
Asymptomatic 2nd degree AV block at intra- or infra- His levels found at electrophysiological study	Class IIa
1st or 2nd degree AV block with symptoms similar to those of pacemaker syndrome or hemodynamic compromise	Class IIa
Asymptomatic type II 2nd degree AV block with a narrow QRS	Class IIa
Neuromuscular diseases with any degree of AV block (including 1st degree AV block), with or without symptoms	Class IIb
AV block in the setting of drug use and/or drug toxicity when the block is expected to recur even after the drug is withdrawn	Class IIb

dycardia. It is of utmost importance to assess for the etiology of the bradycardia: bradyarrhythmia due to a non-essential drug therapy would require drug therapy cessation, and if due to reversible cause (e.g., Lyme disease, increased vagal tone, hypoxia in sleep apnea syndrome in absence of symptoms), would require treatment of underlying cause. Finally, an appropriate diagnosis of the type or level of block is mandatory. Asymptomatic 1st degree, type I 2nd degree AV block at the supra-His (AV node) level, and fascicular block without AV block, do not need a pacemaker.

Table 23.3 Indications for permanent pacing in chronic bifascicular block [1]

Indication	Strength of indication
Advanced 2nd degree AV block or intermittent 3rd degree AV block	Class I
Type II second-degree AV block	Class I
Alternating bundle-branch block	Class I
Syncope not demonstrated to be due to AV block when other likely causes have been excluded, specifically ventricular tachycardia	Class IIa
Incidental finding at electrophysiological study of a markedly prolonged HV interval >100 ms in asymptomatic patients	Class IIa
Incidental finding at electrophysiological study of pacing-induced infra-His block that is not physiological.	Class IIa
Neuromuscular diseases with bifascicular block or any fascicular block, with or without symptoms	Class IIb

Equipment

The basic equipment required for a permanent pacemaker insertion includes: fluoroscope, topical anesthesia (1–2% lidocaine or bupivacaine), instrument tray, pacing system analyzer, introducer kit, suture material, electric cautery, external pacemaker, antimicrobial flush and saline for pocket irrigation. A single-plane fluoroscopy using anteroposterior, 30° right anterior oblique, and 45° left anterior oblique views is used. A pacemaker system consists of two major components: a pulse generator and one or more electrodes. The pulse generator (Fig. 23.1) is the "battery" component of the pacemaker and it provides the electrical impulse for the myocardial stimulation. The electrodes, also known as "leads" (Fig. 23.2a), deliver the electrical impulse from the generator to the myocardium. Currently, the most common cardiac pacing system utilizes transvenous electrodes (leads). However, there are certain clinical situations wherein transvenous leads are not possible (i.e., infection, venous thrombosis/stenosis). In these situations, the epicardial or leadless pacing systems may be considered. A full discussion of these types of pacing system is beyond the scope of this chapter.

Technique

The implantation usually involves a combination of local anesthesia and conscious sedation. The pacing generator is typically placed subcutaneously, superficial to the pectoralis, however, under certain conditions, it may also be placed subpectoral/infra-mammary, or intra-abdominal (i.e., surgically via thoracotomy).

Antibiotic prophylaxis, either with cefazolin or vancomycin, is a standard for device implantation. A central vein: subclavian, internal jugular, or axillary vein, is

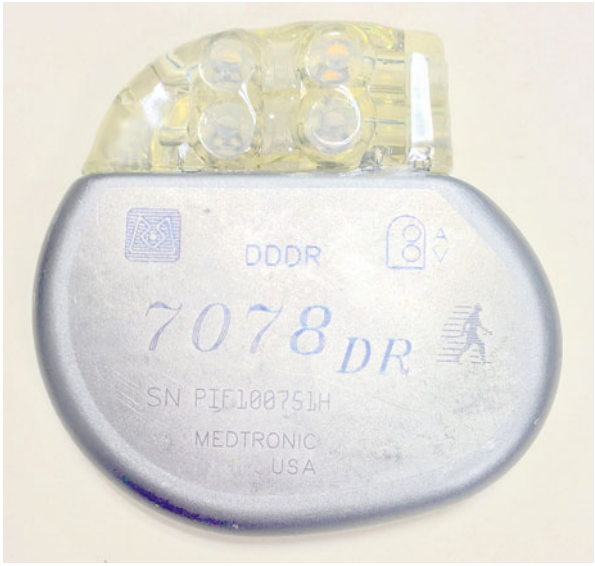

Fig 23.1 Example of a pacemaker generator

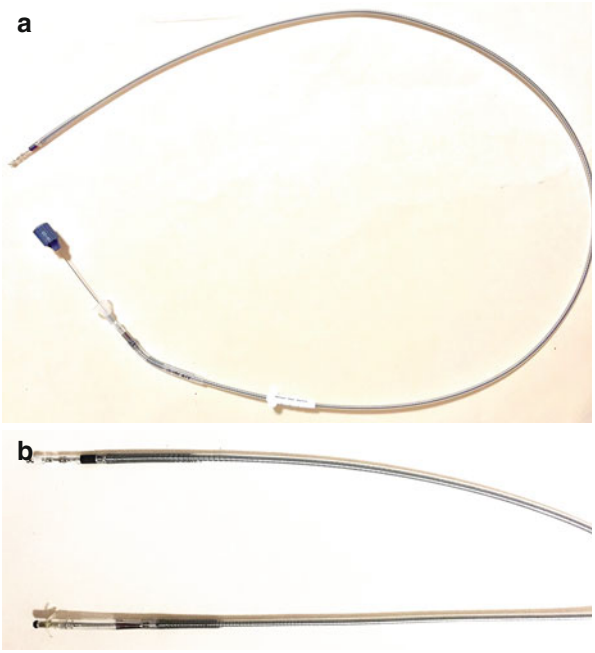

Fig. 23.2 (**a**) Example of an intravenous lead. (**b**) Two types of lead tips: helical screw (*above*) and grappling hook (*below*)

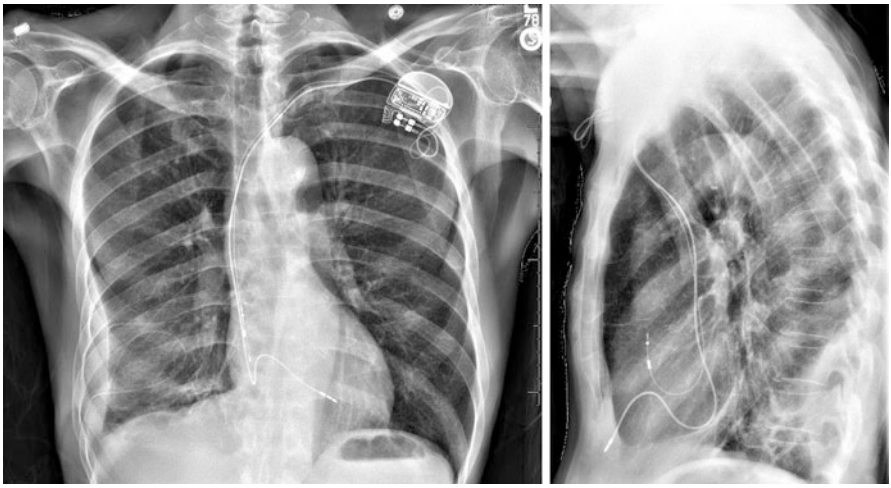

Fig. 23.3 Chest radiograph PA and lateral of a patient with dual chamber pacemaker

access via percutaneous approach. A venous cut down of the cephalic vein may also be done. After venous access is obtained, a guidewire is advanced and subsequently, a sheath and dilator are advanced. The pacemaker lead is then advanced to the chamber of interest (i.e., right atrium, right ventricle). Usually, the ventricular lead is positioned before the atrial lead to prevent its dislodgment.

Once the correct lead positioning is confirmed, lead is affixed to the endocardium either passively with tines (grappling hook) or actively via a helical screw located at the tip (Fig. 23.2b). Pacing and sensing thresholds and lead impedances are measured with the pacing system analyzer. Pacing is also performed at 10 V to assess for diaphragmatic stimulation. After confirmation of lead position and threshold, the proximal end of the lead (s) is then secured to the underlying tissue and connected securely to the pulse generator. The pacemaker pocket is usually irrigated with antimicrobial solution. The incision is closed in layers with absorbable sutures and skin with either adhesive strips or skin glue. An arm sling is applied to the unilateral arm for 12–24 h to limit movement. A post-procedure chest radiograph is usually done for lead position confirmation and to rule out pneumothorax (Fig. 23.3). On the following day, postero-anterior (PA) and lateral chest radiographs will again be done to confirm lead positions and exclude any delayed pneumothorax.

Data Interpretation

A universal pacing code system, also known as NBG pacemaker code, is used to facilitate the understanding of pacemakers. It describes the five-letter code for operation of implantable pacemakers and defibrillators.

Position I reflects the chamber (s) paced. "**A**" indicates the atrium, "**V**" indicates the ventricle, and "**D**" means dual chamber (i.e., both atrium and ventricle).

Position II refers to the chamber (s) sensed. The letters are the same as those for the first position: "**A**", "**V**",or "**D**". An addition option "**O**" indicates an absence of sensing. If a device is programmed in this mode, it will pace automatically at a specific rate, ignoring any intrinsic rhythm.

Position III refers to how the pacemaker responds to a sensed event. "**I**" indicates that a sensed event inhibits the output pulse and causes the pacemaker to recycle for one or more timing cycles. "**T**" indicates that the output pulse is triggered in response to a sensed event. "**D**" indicates dual modes of response and is restricted to dual chamber systems.

Position IV reflects rate modulation, also known as rate adaptive or rate responsive pacing. "**R**" indicates that the pacemaker has rate modulation and incorporates a sensor to adjust its programmed paced heart rate in response to patient's activity. "**O**" indicates that rate modulation is either unavailable or disable.

Position V is rarely used and specifies only the location of multisite pacing or absence thereof. Multisite pacing is defined as stimulation sites in both atria, both ventricles, more than one stimulation site in any single chamber, or a combination of these. "**O**" indicates no multisite pacing. "**A**" means multisite pacing in the atria. "**V**" means multisite pacing in the ventricles, and "**D**" for both atrium and ventricle. The most common application of multisite pacing is biventricular pacing.

Complications

Although considered a minimally invasive procedure, the incidence of complications in modern pacing therapy is still substantial. Permanent pacemaker placement poses various risks ranging from minor to serious life-threatening complications. These complications may be classified according to severity (minor or major), component of pacing system involved (lead, generator/pocket, patient), or to timing of occurrence: in-hospital or acute, sub-acute, or late.

Acute complications occur peri-procedural or in-hospital. Pneumothorax may occur in 1–3 % in patients undergoing pacemaker implantation. Due to this known complication, chest radiographs are performed immediately after, and often, the day after the procedure. Vascular access complications may also occur. Direct subclavian vein punctures are associated with a higher incidence of pneumothorax and lead damage from subclavian crush syndrome. The axillary venous puncture approach and cephalic venous cut down, on the other hand, are associated with lower incidence of pneumothorax and lead damage. Myocardial perforation has been reported to occur in 1 % of patients, with the asymptomatic subclinical perforation occurring to as much as 15 %. Device pocket hematoma is also a common complication. It has an incidence of approximately 5 %, with a higher incidence in patients on anticoagulation or antithrombotic medications. Finally, in-hospital death generally occurs in less than 1 % of pacemaker implantations [3].

Subacute post-implantation complications occur after hospital discharge and less than 30 days after placement. During this period, several types of pacemaker and lead function/failures have been reported: failure to capture, failure to output, undersensing, and inappropriate pacemaker rate [3].

Late complications occur more than 30 days after placement. The most common complications include infection, device/lead advisories, lead function problems/failures, venous thrombosis or stenosis. Localized infection involving the device pocket may occur up to 60 % of the patients, with the rest presenting as endovascular infection. Device malfunction leading to device explantation occurs in <1 % of patients. A rise in capture threshold may occur beyond 6 weeks of implantation. As this threshold rises, it may exceed the maximum output of pulse generator. This phenomenon is called "exit block". Venous stenosis, less commonly thrombosis, has also been reported after implantation of pacing leads [3].

Clinical Vignettes

Case 1

A 76 year old man with hypertension and dyslipidemia comes in for an annual check-up. He is feeling well, active, and runs yearly in a marathon. His medications include lisinopril and atorvastatin. His resting heart rate was found to be 43 beats/min with blood pressure of 120/75. An ECG was done which shows sinus bradycardia 44 beats per minute, with normal PR and QRS intervals.

The most important feature in this patient's history is the absence of any symptom. It is a Class III recommendation to implant a permanent pacemaker for SND in asymptomatic patients. ECG monitoring may be done should any symptom arise and if there is a need to correlate it with bradyarrhythmia. Given the lack of symptoms and patient's high level of activity, pacemaker is not indicated.

Case 2

A 68 year old woman with hypertension and coronary artery disease, presented to the hospital for two episodes of syncope. She has been having palpitations and several pre-syncopal episodes for 3 months. Upon arrival, patient is awake and alert. A rhythm strip was obtained which showed atrial fibrillation with a ventricular rate of 185 bpm. Her BP was 115/70. Metoprolol 2.5 mg IV was given and patient became pre-syncopal. She then had a heart rate of 30 bpm and a BP of 90/60. An hour later, she was again in atrial fibrillation with a ventricular rate of 170 bpm.

This association of paroxysmal atrial fibrillation and sinus bradycardia, accompanied by symptom, is worrisome for a "tachy-brady syndrome", a type of sinus

node dysfunction. Individuals with tachy-brady syndrome have diseased SA nodes and often display exaggerated overdrive suppression. Given the patient's symptoms and sinus node dysfunction, a pacemaker is recommended.

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Chapter 24
Biventricular Pacing

Chris Healy and Juan F. Viles-Gonzalez

Introduction

As left ventricular (LV) systolic dysfunction progresses to clinical heart failure, it is frequently accompanied by impaired electromechanical coupling. This may further impair ventricular contractility. Prolonged interventricular and intraventricular conduction results in regional mechanical delay within the LV and can cause reduced ventricular systolic function, functional mitral regurgitation, and ventricular remodeling/dilation. Modification of ventricular electromechanical delay with multisite ventricular pacing (commonly called biventricular [BiV] pacing or cardiac resynchronization therapy [CRT]) can improve ventricular systolic function, induce favorable remodeling, decrease heart failure hospitalizations, and reduce mortality [1, 2]. Currently, CRT is indicated for mortality reduction and symptom improvement in patients with systolic heart failure and LV dyssynchrony as evidenced by a wide QRS complex on electrocardiogram (EKG). Numerous markers of LV dyssynchrony have been described, including a number of echocardiographic measurements. However, the marker which best predicts outcomes following CRT is the width/morphology of the QRS complex. As such, the strength of the indication for CRT is dependent on a patient's QRS duration and morphology as well as New York Heart Association (NYHA) heart failure class.

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Indications

Per the most recent ACC/AHA guidelines, the only Class I indication for CRT is for patients in sinus rhythm with LV ejection fraction (LVEF) ≤35 %, a QRS duration ≥150 ms, left bundle-branch block (LBBB) morphology, and NYHA class II, III, or ambulatory IV heart failure. Please refer to Table 24.1 for a full listing of all the indications for CRT. It is important to note that all of these recommendations refer to patients who are already on guideline directed medical therapy [3].

Contraindications

There are two circumstances under which CRT carries a Class III recommendation (no benefit and may cause harm). These are patients who do not fulfill implant criteria (NYHA class I or II symptoms, non-LBBB pattern, and QRS duration <150 ms) and patients with estimated survival <1 year based on comorbidities and/or frailty [3].

Equipment

CRT devices, like the majority of cardiac implantable electronic devices, consist of two basic components, the pulse generator and the leads (Fig. 24.1). There are two main categories of CRT devices, BiV pacemakers and BiV ICDs. The

Table 24.1 Indications for cardiac resynchronization therapy

Indication	Strength of indication
Sinus rhythm, LVEF ≤35 %, LBBB, QRS duration ≥150 ms, and NYHA class II, III, or ambulatory IV symptoms	Class I
Sinus rhythm, LVEF ≤35 %, LBBB, QRS duration 120–149 ms, and NYHA class II, III, or ambulatory IV symptoms	Class IIa
Sinus rhythm, LVEF ≤35 %, non-LBBB pattern, QRS duration ≥150 ms, and NYHA class III or ambulatory IV symptoms	Class IIa
Atrial fibrillation, LVEF ≤35 %, patient requires ventricular pacing, and AV nodal ablation or pharmacologic rate control will allow near 100 % ventricular pacing with CRT	Class IIa
LVEF ≤35 % and undergoing new or replacement device placement with anticipated requirement for significant (>40 %) ventricular pacing	Class IIa
Sinus, rhythm, LVEF ≤30 %, LBBB, QRS duration ≥150 ms, ischemic etiology of heart failure, and NYHA class I symptoms	Class IIb
Sinus, rhythm, LVEF ≤35 %, non-LBBB pattern, QRS duration 120–149 ms, and NYHA class III or ambulatory IV symptoms	Class IIb
Sinus, rhythm, LVEF ≤35 %, non-LBBB pattern, QRS duration ≥150 ms, and NYHA class II symptoms	Class IIb

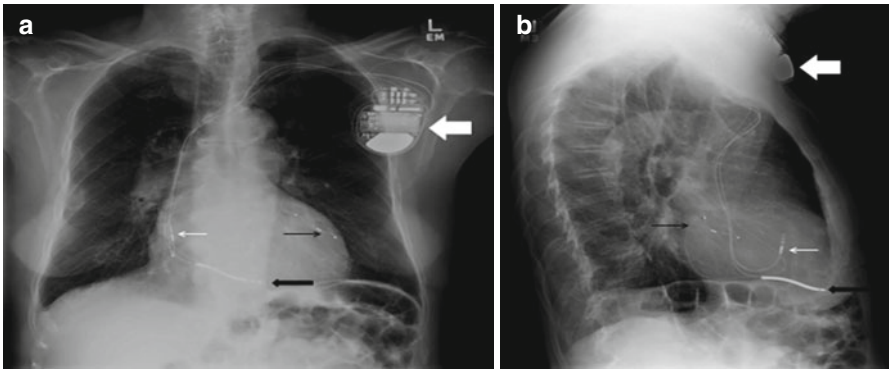

Fig. 24.1 PA and lateral radiographic images of a biventricular implantable cardioverter defibrillator. PA (Panel **a**) and lateral (Panel **b**) chest x-rays showing a biventricular implantable cardioverter defibrillator. Both images show the device (*thick white arr*ow) implanted in the left chest, the atrial lead (*thin white arrow*) positioned in the right atrial appendage, the right ventricular lead (*thick black arrow*) positioned in the right ventricular apex, and the left ventricular lead (*thin black arrow*) positioned in a lateral branch of the coronary sinus

majority of devices implanted are BiV ICDs, as the majority of patients who are candidates for CRT also have an indication for an ICD for primary prevention of sudden cardiac death.

CRT devices are typically larger than standard pacemakers or ICDs. However, even the largest devices are smaller than an average deck of playing cards. The device contains two main components, the electronics that control the device function and a compact battery.

All CRT devices have at least two leads, and most have three leads. Typically there is an atrial lead to facilitate AV synchrony, though in some circumstances this may not be necessary (chronic atrial fibrillation). By definition, these devices must have two ventricular leads. Typically one lead is placed in the right ventricular (RV) apex or elsewhere in the RV along the interventricular septum. Unique to BiV devices, is the presence of a pacing lead in the coronary sinus. The coronary sinus lead can have as many as four pacing electrodes on it (Fig. 24.2). This allows for multiple possible pacing vectors, so as to produce the most synchronous contraction of the LV.

Technique

Placement of a CRT device involves two procedural components, creation of the pocket where the pulse generator will sit and placement of the leads. The procedure is performed in a sterile environment (either an electrophysiology laboratory or an operating room). The most common locations for the device pocket are the left and right chest. The device is typically placed prepectorally. However, the device can also be placed below the pectoralis muscle if necessary (thin patient, desire for better cosmetic result, etc.). This results in a relative increase in the risk of

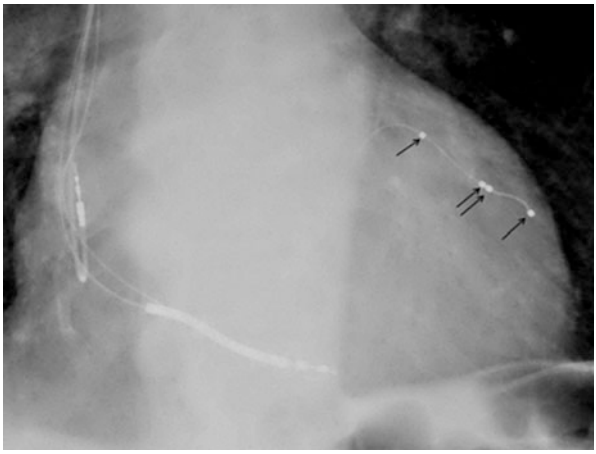

Fig. 24.2 Radiographic image of coronary sinus lead. PA chest x-ray showing a quadripolar lead implanted in a lateral branch of the coronary sinus. Note the four pacing poles marked by the *black arrows*. This allows for numerous possible pacing configurations

post-procedure bleeding. The device can be placed in the abdomen instead of the chest wall when necessary, though this is uncommon.

Whenever possible, all leads are placed via the transvenous route. Typically access is obtained into the axillary or subclavian vein and the right atrial (RA) and RV leads are passed via the superior vena cava to their ultimate locations. The coronary sinus lead is typically the most challenging lead to place. First, a guiding catheter is placed via the RA into the coronary sinus. Then, a balloon-tipped catheter is advanced through the guiding catheter into the coronary sinus. With the balloon inflated in the proximal coronary sinus, a venogram of the coronary sinus is obtained. This provides anatomical information, so that the most ideal branch of the coronary sinus for lead placement can be determined. The branch which allows for the most lateral location of the lead is commonly chosen. Next, a wire is advanced through the guiding catheter and positioned in the chosen coronary sinus branch. The coronary sinus lead is then advanced over the wire to its ultimate location. As with any pacing system, all leads must be tested after placement for adequate sensing, impedance, and pacing thresholds.

Occasionally, the leads cannot be placed in adequate locations for various reasons (central venous stenosis, unfavorable coronary sinus anatomy, etc.). In these circumstances, patients may require epicardial lead placement via an open, surgical approach.

When all leads have been placed, they are connected to the device which is secured in the pocket and the incision is closed.

Data Interpretation

The most important response to placement of a CRT device is the patient's functional capacity. Many coronary sinus leads have multiple electrodes, and if a patient has a suboptimal response to CRT a different pacing vector for the coronary sinus lead can be chosen. Different protocols exist for echocardiographic or SPECT guided CRT optimization. However, data on these approaches is currently limited.

Complications

Placement of a CRT device is an invasive procedure that carries the risk of serious and possibly life threatening complications. The most common complications include device infection and bleeding at the incision site or in the pocket. Bleeding can typically be controlled with the use of a pressure dressing, but occasionally large pocket hematomas require drainage. Infection is a more serious complication, and complete extraction of all device components is recommended whenever possible in addition to antibiotic therapy.

Less common complications include injury to the SVC or other major blood vessels; perforation of the RA, RV, interventricular septum, or coronary sinus; pericardial effusion; cardiac tamponade; arrhythmia; and death. Pericardial effusions can usually be treated conservatively with observation. However, if there is evidence of cardiac tamponade, percutaneous drainage is required. In rare cases, emergent surgery may be necessary.

Clinical Vignettes

Case 1

A 55 year old man with ischemic cardiomyopathy of 4 years duration presents to clinic. He reports stable DOE with walking one block. His medications include lisinopril, metoprolol, aspirin, simvastatin, spironolactone, and furosemide. He had a single lead ICD placed 2 years ago for primary prevention of sudden cardiac death. His EKG shows sinus rhythm with a LBBB and a QRS duration of 153 ms. His echocardiogram shows a LVEF of 25 %.

The key question is: What is the most appropriate next step? It is premature for referral for transplant or to consider hospice and adding additional medical therapy, such as with an ARB, is unlikely to provide much benefit.

The best course would be to upgrade the device to a BiV system. He has a Class I indication for CRT (systolic heart failure, NYHA class III, sinus rhythm, LBBB, QRS $\geq$ 150 ms, and EF $\leq$ 35 %).

Case 2

In which of the following patients undergoing device implantation would implantation of a CRT device be reasonable?

A. *85 year old man referred for AAI pacemaker implantation for the treatment of symptomatic sick-sinus syndrome*

B. *56 year old woman with nonischemic cardiomyopathy, LVEF of 25 %, and a QRS duration of 95 ms referred for ICD implantation for the primary prevention of sudden cardiac death*
C. *45 year old man with nonischemic cardiomyopathy and LVEF 40–45% referred for dual-chamber pacemaker implantation in complete heart block*
D. *None of the above*

The correct answer is C, a 45 year old man with nonischemic cardiomyopathy and LVEF 40–45% referred for dual-chamber pacemaker implantation in complete heart block. He already has evidence of cardiomyopathy (EF 40–45 %) and he would be expected to pace nearly 100 % of the time (complete heart block). He would be at risk of deterioration in his EF from chronic RV pacing, and thus it would be reasonable to consider a CRT device. The first patient's indication for a pacemaker is sick-sinus syndrome and thus he would not be expected to pace the ventricle. The second patient has a narrow QRS and no pacing indication. Neither of these patients would likely benefit from CRT.

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Chapter 25
Implantable Cardioverter Defibrillators (ICD)

Camilo A. Gomez

Implantable cardioverter-defibrillators (ICD) are devices designed for the prevention of sudden cardiac death (SCD) in selected patients. SCD often occurs as a consequence of malignant ventricular arrhythmias as ventricular tachycardia (VT) or VT that degenerated in ventricular fibrillation (VF). Current ICD's are capable to deliver multiple therapies, which incorporate antitachycardia pacing (ATP), cardioversion, and defibrillation, also provide support in episodes of bradycardia or heart block with a rate-response pacing and automatic switching mode function. Modern devices are able to provide resynchronization therapy, an important option in selected patients requiring advanced heart failure therapies [1].

Indications

ICD's are currently indicated for the prevention of SCD. In survivors of VT/VF cardiac arrest, ICD's are the optimal treatment for "secondary prevention" of patients. ICD's are also recently used as "primary prevention" in patients who are considered to be at high risk for VT/VF.

The use of ICD as secondary prevention is supported by multiple randomized controlled trials and has the benefit in patients with marked reduction of left ventricular function. The use of ICD for primary prevention currently represents more than 80 % of its implantation.

There are other high risk conditions that are known to be associated with SCD, as patients with structural heart disease or inherited channelopathies.

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Consideration of ICD therapy, particularly those for primary prevention apply only to patients who are receiving optimal medical therapy, have a reasonable expectation of survival with good functional status for more than 1 year, and an independent risk assessment, including patient preference (See Table 25.1) [2, 3].

Table 25.1 ACC/AHA/HRS 2008 guidelines for device-based therapy of cardiac rhythm abnormalities

CLASS I INDICATIONS evidence and/or general agreement that ICD's are useful and effective
1. Survivors of cardiac arrest due to ventricular fibrillation or hemodynamically unstable sustained VT after evaluation to define the cause of the event and to exclude any completely reversible causes
2. Structural heart disease and spontaneous sustained VT, whether hemodynamically stable or unstable
3. Syncope of undetermined origin with clinically relevant, hemodynamically significant sustained VT or ventricular fibrillation induced at electrophysiological study
4. LVEF less than or equal to 35 % due to prior myocardial infarction who are at least 40 days post–myocardial infarction and are in NYHA functional Class II or III
5. Nonischemic dilated Cardiomyopathy who have an LVEF less than or equal to 35 % and who are in NYHA functional Class II or III
6. LV dysfunction due to prior myocardial infarction who are at least 40 days post–myocardial infarction, have an LVEF less than or equal to 30 %, and are in NYHA functional Class I
7. Nonsustained VT due to prior myocardial infarction, LVEF less than or equal to 40 %, and inducible ventricular fibrillation or sustained VT at electrophysiological study
CLASS IIa INDICATIONS conflicting evidence about the usefulness of ICD therapy, with the weight of evidence/opinion in favor of usefulness/efficacy
1. Reasonable for patients with unexplained syncope, significant LV dysfunction, and nonischemic cardiomyopathy
2. Reasonable for patients with sustained VT and normal or near-normal ventricular function
3. Reasonable for patients with hypertrophic cardiomyopathy who have 1 or more major risk factor for SCD
4. Reasonable for the prevention of SCD in patients with arrythmogenic RV dysplasia who have 1 or more risk factors for SCD
5. Reasonable to reduce SCD in patients with long-QT syndrome who are experiencing syncope and/or VT while receiving beta blockers
6. Reasonable for non hospitalized patients awaiting for transplantation
7. Reasonable for patients with Brugada syndrome with syncope or who have documented VT that has not resulted in cardiac arrest
8. Reasonable for patients with catecholaminergic polymorphic VT who have syncope and/or documented sustained VT while receiving beta blockers
9. Reasonable for patients cardiac sarcoidosis, giant cell myocarditis, or Chagas disease
CLASS IIb INDICATIONS usefulness/efficacy is less well established by evidence/opinion
1. Considered in patients with nonischemic heart disease who have an LVEF of less than or equal to 35 % and who are in NYHA functional class I
2. Considered for patients with long-QT syndrome and risk factors for SCD
3. Considered in patients with syncope and advanced structural heart disease in whom through invasive and noninvasive investigations have failed to define a cause
4. Considered in patients with a familial cardiomyopathy associated with SCD
5. Considered in patients with LV noncompaction

From Ref. [1]

Table 25.2 CLASS III conditions for which there is a general agreement that ICD's are not useful and possibly harmful

1. Not indicated for patients who do not have a reasonable expectation of survival with an acceptable functional status for at least 1 year, even if they meet ICD implantation criteria
2. Not indicated for patients with incessant VT or VF
3. Not indicated in patients with significant psychiatric illnesses that may be aggravated by device implantation or that may preclude systematic follow-up
4. Not indicated for NYHA class IV patients with drug-refractory congestive heart failure who are not candidates for cardiac transplantation or CRT-D
5. Not indicated for syncope of undetermined cause in a patient without inducible ventricular tachyarrhythmias and without structural heart disease
6. Not indicated when VF or VT is amenable to surgical or catheter ablation (e.g., atrial arrhythmias associated with the Wolff-Parkinson-White syndrome, RV or LV outflow tract VT, idiopathic VT, or fascicular VT in the absence of structural heart disease)
7. Not indicated for patients with ventricular tachyarrhythmias due to a completely reversible disorder in the absence of structural heart disease (e.g., electrolyte imbalance, drugs, or trauma)

From Ref. [1]

Contraindications

Major ICD implantation contraindications are included in the ACC/AHA/HRS guidelines (See Table 25.2). Other contraindications are: Hemodynamically unstable patients, in the setting of acute myocardial ischemia or hypoxia, post coronary artery bypass surgery, in the setting of active infection in the chest wall or bloodstream infections, with electrolyte imbalances and with drug toxicities [2, 3].

Equipment

The physical components of the implanted system consist of:

1. ICD generator: consist of a battery, capacitor, DC-DC converter, a microprocessor, and telemetry communication coils an their connections (Fig. 25.1).
2. Sensing and the pacing leads, and one or more high energy leads (also known as electrodes). These elements deliver the three essential functions of the ICD, detection, tachycardia therapy and bradycardia pacing (Fig. 25.2) [3, 4].

Technique

Implantation of the ICDs system involves its subcutaneous insertion, positioning of the leads and finally testing the sensing and pacing functions. Usually are implanted in the left pre-pectoral area with the purpose to create a left-to-right vector for defibrillator shocks, the right pectoral area may be used in selected

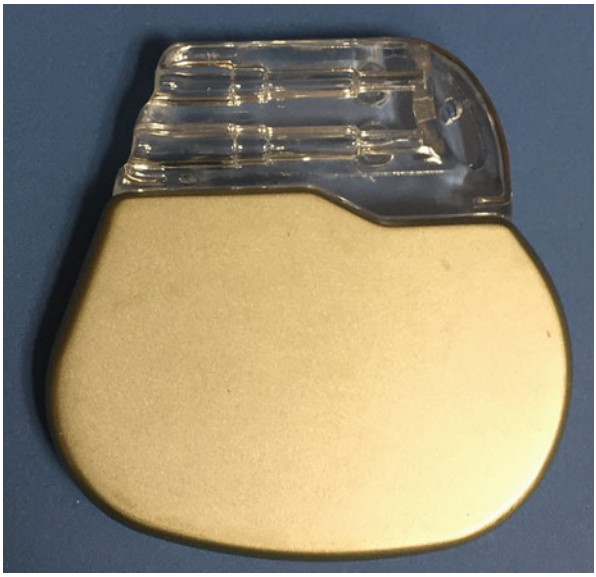

Fig. 25.1 ICD generator that is implanted subcutaneously in the prepectoral region, it is replaced when battery ends life. Has and has an upper portion with connectors were the leads are attached

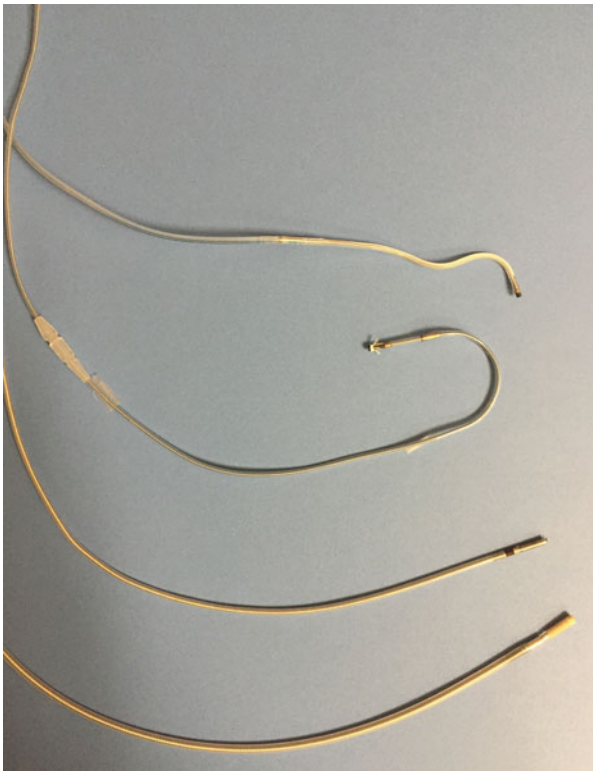

Fig. 25.2 Different examples of leads that has pacing and sensing capabilities, which exist in different shapes according the chamber were they are placed (atrium or ventricles) and distal portions with different end tip electrodes for active or passive fixation

left-handed patients or when left venous access is impeded, in cases of infection or any other abnormalities. Initially with an standard sterile technique, an incision is made in the left pre-pectoral area, the subclavian, cephalic or both veins are dissected, once the vein (s) are exposed leads can be inserted transvenously. Cephalic vein access is preferred over subclavian because carries a smaller risk of arterial puncture, pneumothorax and subclavian crush injury at long term, which occur when the inserted leads are trapped within the subclavius muscle or the costoclavicular complex. Once the vein is incised the leads are advanced under fluoroscopic guidance into the right heart until reach the pulmonary artery. then the lead is pulled back and fixed in the right ventricle (RV) apex. Subsequently lead positioning, electrocardiogram stability and adequate sensing and pacing parameters are confirmed. When dual-chamber ICD are implanted require the insertion of an additional atrial lead, it is placed following the insertion of the ventricular lead, and should be placed in the high right atrium or in the superior aspect of the atrial appendage to avoid cross-talk between atrial stimuli and the ventricular detection circuits. The sleeve of the lead is anchor using silk sutures to the surrounding muscular fascia.

After vascular access, a pocket is created were the generator will be seated, it should be of adequate size for the device to avoid device erosion, migration or seroma formation, it is usually on the medial aspect anterior to the plane of the pectoral fascia, it should be inferior to the clavicle and in a medial position to avoid restriction of movement of the shoulder and the arm. The leads then are connected to the generator header, insertion in the correct ports and securely connection is verified, pocket is clean for tissue, secretions and blood that may be interposed. An antibiotic solution is used to irrigate the port and the generator is placed in the pocket. Device is tested for sensing, pacing and DFT, once adequate device function is confirmed the pocket is closed with sterile suture.

Patient's arm is placed in a sling, lead position is confirmed by immediate postop chest x ray and also to rule out complications as pneumothorax. Before discharge postero-anterior and lateral chest x ray are performed (Fig. 25.3) [4, 5].

Data Interpretation

Patients are follow up with routine clinical visits usually at quarterly intervals. Devices are interrogated to evaluate its function, battery depletion, alarms and events. Also gives the advantage of monitoring comorbidities measuring physiological parameters in conditions as heart failure and atrial fibrillation. Furthermore there are devices with remote internet based functions that permits automatically transmit stored data by wireless telemetry.

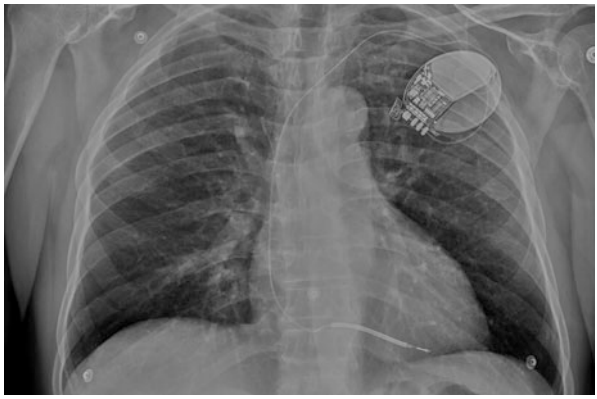

Fig. 25.3 X-ray of a patient post single chamber ICD implantation. All parts of the ICD system can be appreciated, the generator with a single lead directed and attached in position at the apex of the right ventricle

Complications

- Surgical related: Ranges between 3 and 5 % for single or dual-chamber ICDs. Complications are similar to those of pacemaker implantation: cardiac perforation, tamponade, vascular perforation, pneumothorax, hematoma, infection and lead dislodgment. Pulse generator changes adds a 1–4 % risk of infection, and complications can increase up to 15 % when a new transvenous lead is added at the time of replacement.
- Late complications: less than 4 % and include lead fracture, generator migration/erosion, generator failure, thrombosis, and complications related to defibrillation testing as myocardial or cerebral ischemia, electromecanical dissociation and refractory VF (4, 6).

Clinical Vignettes

Case 1

A 55 year old male was admitted with substernal chest pain radiated to the left arm for 30 min. Vitals at admission were blood pressure of 88/50, heart rate of 98 and respiratory rate of 22. The electrocardiogram showed ST elevation in anterior leads (V1–V4), troponin was found elevated. Emergent cardiac catheterization was performed with percutaneous intervention of a completely occluded left anterior descending artery by a thrombus. Post MI echocardiogram showed an ejection fraction of 15–20 % with severe akinesis of the anterior wall. The patient was discharged with dual antiplatelet agents, beta blocker, statin and ace- inhibitor. Forty days post MI was seen in the clinic, echocardiogram was performed and showed an EF of 20–25 %.

The patient has cardiomyopathy, with an EF less than 35 % and is 40 days post MI, is functional class II and therefore should received an ICD for primary prevention of SCD.

Case 2

A 30 year old male with no known medical conditions, suddenly collapse at home, CPR was started by one of his family members. When EMS arrived at the scene, he was found with ventricular fibrillation and was shocked 2 times before the return of spontaneous circulation. He was taken to the hospital, and admitted to the cardiac intensive care unit. Initial echocardiogram showed and EF of 10 % with global hypokinesis post cardiac arrest. He progressively recovered over the following 2 weeks without neurological deficits, but the cause of cardiac arrest couldn't be clarify after extensive cardiac workup. Repeat echocardiogram showed an EF of 55 % with a normal ventricular wall motion.

An ICD is indicated in patients such as this, who are survivors of cardiac arrest due to VF or hemodynamically unstable sustained VT after evaluation to define the cause of the event and to exclude any completely reversible causes.

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Chapter 26
Pacemaker Interrogation and Programming

D. Michael Farmer and Munther Homoud

Introduction

Pacemaker programming and interrogation is essential not only in the immediate post-implantation period, but also at regular follow-up visits throughout the life of the pacemaker. The implantation of a pacemaker follows a clinical event and it is incumbent upon the physician implanting the device to insure that the device has met its clinical goals. Current pacemakers are endowed with a variety of features to help meet the aforementioned requirement. Hence, patients with pacemakers should be seen regularly and their pacemakers should be interrogated with each visit.

Indications

Pacemaker function post-implant should be observed on cardiac telemetry prior to discharge. In patients who are not pacemaker dependent, an electrocardiogram performed with a magnet applied against the pacemaker will elicit a pacing spike from the chamber being paced.

Following discharge, patients are often seen 1–2 weeks after the implant to assess the site of the incision. The patient will then follow-up in an outpatient setting for pacemaker interrogation in 6 weeks. This follow-up is important because it assesses the rise and subsequent decline in pacing thresholds. The pacemaker generator outputs can then be programmed to outputs lower than those programmed at implant.

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This process preserves generator battery life while providing an adequate safety margin for expected fluctuations in the pacing thresholds.

After this initial outpatient interrogation is performed, Medicare and Medicaid guidelines allow for dual chamber devices to be followed up every 6 months. Patients with single chamber pacemakers who are not pacemaker dependent may follow-up on an annual basis. During these visits, the original indications for pacemaker implant, as well as the need for modification of the existing pacemaker system should be assessed. Modifications may include the need to adjust the lower pacing rate, the upper tracking rate, or the AV interval. The activity sensor may need to be turned on if the patient is complaining of fatigue. The sensor parameters should be tested in the pacemaker clinic by observing the patients' heart rate response to graded activity. The development of new clinical events such as heart failure or the recovery from an acute myocardial infarction may prompt an upgrade of the pacemaker to an implantable cardioverter defibrillator (ICD) or a pacemaker capable of biventricular pacing.

Beyond routine follow up, certain events warrant interrogation of a pacemaker. Pacemaker interrogation should be performed when a clinical event has occurred that could have been cause by pacemaker malfunction, e.g. syncope, or when a clinical event can be further delineated by intra-cardiac electrograms that can be retrieved during pacemaker interrogation. Intra-cardiac electrograms retrieved from pacemakers can be useful in differentiating supraventricular tachycardias from ventricular tachycardias, as well as excluding arrhythmias as a source of syncope in patients with a pre-existing pacemaker.

A variety of procedures performed in the hospital may interfere with the pacemaker's normal function or may damage a pacemaker. The pacemaker should be interrogated before and after certain types of procedures are completed. Examples of such procedures include radiofrequency ablation, cardioversion, diathermy, electroconvulsive therapy (ECT) and lithotripsy. Patients scheduled for surgery who are pacemaker dependent should have their pacemakers programmed to an asynchronous mode if the use of diathermy is anticipated. This would eliminate the fear that diathermy would inhibit pacing. The patient should be continuously monitored in case asynchronous pacing induces an arrhythmia. At the time of this writing, MRI scanning in patients with pacemakers should be restricted to patients who have received pacemakers and leads that have been approved for conditional use in the MR environment. It is important for the provider ordering the MRI confirm that the patient not have an older, non MRI compatible lead before proceeding with the study. If a patient with a pacemaker lacking conditional approval inadvertently has an MRI performed, the pacemaker should be promptly interrogated to determine its status.

Equipment

Pacemaker interrogation requires company-specific device programmers. Pacemaker interrogation and programming cannot occur between products from two different device companies. Although, there are several pacemaker companies

Fig. 26.1 Pacemaker interrogation

(Medtronic®, Boston Scientific®, Biotronik® and St. Jude Medical®) widely used in the US, the techniques for pacemaker interrogation and concepts for pacemaker data interpretation are similar. Each programmer is equipped with a programming head, surface ECG leads, power cord, printer, and touch-screen programmer (Fig. 26.1). Clinics where pacemaker interrogation is performed must be equipped with an external defibrillator in the rare event the patient develops a life threatening arrhythmia.

Technique

Pacemaker interrogation can be performed in either the sitting or supine position. ECG surface leads should be connected to the patient and the programmer using the device specific electrodes. The pacemaker programming head should be placed over the patient's pacemaker. The pacemaker is usually located in either pectoral region, or rarely in the abdomen. The programming head should be positioned in a stable manner, such that constant telemetry can be maintained between the device and programmer. Once the programmer is turned on, interrogation can then proceed. Many newer programmers have automated follow up algorithms that proceed once prompted by the operator.

Data-Interpretation

Once device interrogation has occurred, baseline data should be ascertained and lead testing should be performed. This data and testing results are essential in evaluating a variety of pacemaker malfunctions. All available data should be systematically retrieved and evaluated during each pacemaker interrogation. The core of this evaluation includes battery life, lead impedances, as well as capture and sensing thresholds. The underlying rhythm of the patient, as well as lead configuration (unipolar or bipolar) should also be determined. In addition, most pacemakers have stored electrogram events that need to be retrieved and evaluated at each interrogation.

Battery Status

Pacemaker battery status should be evaluated with each interrogation. At the beginning of life (BOL) the battery voltage is approximately 2.8 V (specific values vary from manufacturer to manufacturer), and pacemaker behavior is as programmed. Over the life of the pacemaker, the battery reaches elective replacement indicators (ERI). At ERI, the battery voltage is reduced, but still able to support most if not all of the pacemaker functions. At this point, generator replacement should be scheduled in weeks to months depending upon the degree of dependence upon the pacemaker. As voltage reduces further, battery end of life (EOL) is reached. At this junction, the voltage is unable to support basic pacer function, and immediate generator change is required. It usually takes 3–6 months for the pacemaker battery to reach EOL status after the battery reaches ERI. Another parameter used to determine the pacemaker's battery status is the battery's impedance. As the battery voltage declines, the battery impedance rises.

Lead Impedance

While different leads offer differ impedances, once a lead is implanted, the fluctuation of impedance is very narrow. The lead impedance of each implanted lead should also be measured during each interrogation. Lead impedance is the sum of all factors that retard current flow. Very high lead impedances suggest the existence of lead fractures or a loose connection in the device header (between the lead pin and the set screw). Very low lead impedances suggest insulation failure. The change in impedance from a previous recording is more important than the absolute value of the lead impedance. Changes greater than 300 Ω are abnormal and should prompt further evaluation.

Sensing and Pacing Thresholds

Although many devices have automated evaluations of pacing and sensing thresholds, many require manual pacing and sensing threshold determinations. Sensing is the ability of the pacemaker to detect and respond to intrinsic atrial and ventricular activity. Sensing thresholds are unable to be assessed without the presence of native atrial and/or ventricular activity. Most current programmers will automatically check the amplitude of the underlying atrial or ventricular electrograms by transiently inhibiting pacing or lowering the pacing rate in the respective chambers. This would allow the emergence of the underlying rhythm and measurement of its amplitude as sensed by the pacemaker in its respective chamber. Two other techniques can be used used to evaluate sensing thresholds if the programmer lacks the automated mode. One technique involves recording telemetered electrograms and measuring peak-to-peak amplitudes of the resulting signal. The more common technique utilized in both automated and semi-automated fashions, is to progressively reduce the sensitivity setting of the pacemaker until an inappropriate spike is delivered indicating that the pacemaker no longer senses an intrinsic electrical activity in the chamber being tested. To use this method to assess ventricular sensing manually, the pacing rate needs to be programmed to a rate below the patient's intrinsic heart rate. The patient's dependency upon the pacemaker can also be assessed during this maneuver. By programming the ventricular chamber to a less sensitive mode (increasing the millivolt values) in the VVI mode the sensitivity value (in mV) at which an inappropriate pacer output is displayed corresponds to the sensing threshold of the ventricle. Atrial sensing thresholds can be manually determined in a similar fashion.

The capture threshold is the lowest pacing output that results in consistent capture of myocardium. This capture threshold is a measurement of the least amount of energy that is required to consistently cause myocardial depolarization. This energy is a function of current, voltage and pulse duration or width. Capture is reported in both voltage and pulse duration. Both of these parameters can be independently programmed. When determining capture threshold it is most commonly reported as voltage threshold at a given pulse duration. It can also be reported as pulse duration threshold at a given voltage. The relationship between these two parameters is defined as the strength-duration curve. The curve is automatically created after threshold testing with some Medtronic devices (Fig. 26.2). Manually, capture threshold is determined by pacing the desired chamber at a rate higher than the intrinsic rate while progressively decreasing the output (amplitude or pulse duration) until capture is lost (Fig. 26.3). The lowest voltage at which capture consistently occurs is the capture threshold. Conversely, capture threshold can be testing by progressively decreasing pulse duration. In most patients, especially those who are pacemaker dependent, programming should provide a 2:1 safety margin in voltage threshold. Some pacemaker systems automatically monitor capture thresholds and automatically adjust the output based on detected changes.

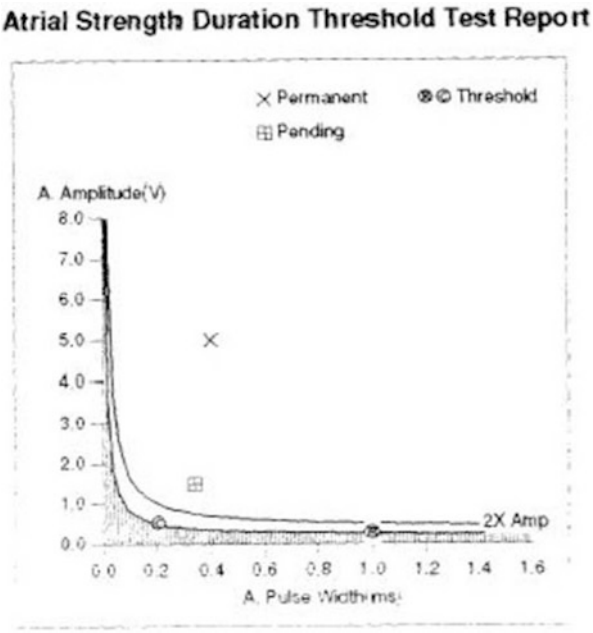

Fig. 26.2 Strength-duration curve

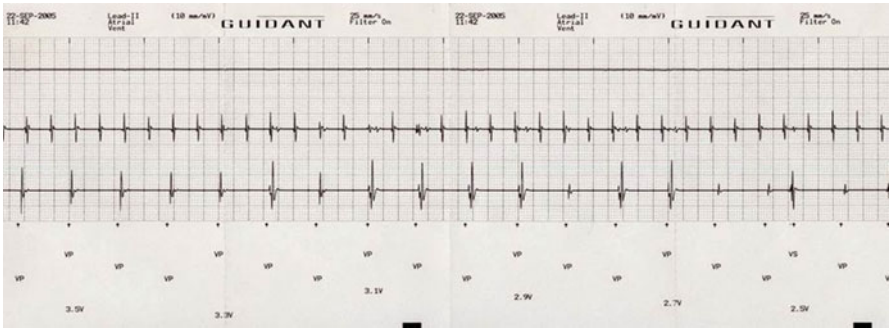

Fig. 26.3 Capture threshold determination. With decreasing output voltage, capture is lost at 2.7 V, noted by absence of ventricular capture at the right side of the electrogram

The basics of pacemaker interrogation are the assessment of battery voltage, lead impedances, sensing thresholds, and capture thresholds. During each pacemaker evaluation it is also important to evaluate all baseline programmed parameters. These parameters include pacing mode, lower rate limit, upper rate limit, AV delay, voltage output, and sensitivity. The inadvertent exposure to eletromechanical interference may result in inadvertent programming of various pacing parameters.

Event Markers and Electrograms

Current devices all have the capability for electrogram storage. Event markers are displayed on the programmer screens and intracardiac electrograms. These event markers report behavior of the pacemaker in regards to paced and sensed events using alphanumeric labeling. The interpretation of these markers during real-time evaluation as well as in the assessment in the evaluation of stored events is crucial in the pacemaker interrogation.

Rate-Adaptive Pacing and Mode Switching

Two additional basic concepts are important to evaluate during pacemaker programming. The DDDR or VVIR modes are rate-adaptive pacing modes. Rate adaptive-pacing provides a heart rate response to meet the increased metabolic requirements for those patients with chronotropic incompetence during physical activity. Commercially available sensors include accelerometers that respond to upper body movement or minute ventilation that responds to changes in transthoracic impedance. They attempt to provide input to the pacemaker modulating the heart rate to meet the body's metabolic requirements. Specific algorithms then convert this data to a heart rate response in attempt to simulate the heart's normal response. Programming the DDDR or VVIR mode to DDD or VVI, respectively, can turn off these sensors.

Most patients known to have supraventricular tachycardias, especially atrial fibrillation, have mode switching programmed on. Without mode-switching algorithms, inappropriate tracking of rapid atrial activity would cause pacing at the upper rate limit. When rapid atrial activity occurs, as in atrial fibrillation, the pacing mode is switched from the DDDR to VVIR or DDIR mode depending on pre-programmed parameters.

Troubleshooting

The two following clinical vignettes give two examples of how pacemaker interrogation can be useful in clinical diagnosis. Figure 26.4 is a real time intra-cardiac electrogram with event markers from an 82-year-old patient s/p permanent pacemaker who presented to pacemaker clinic for routine follow-up. The intracardiac electrograms reveal atrial undersensing as clearly indicated by the absence of atrial channel markers when native activity is present. By decreasing the sensing millivolt value, the sensitivity is increased and normal pacing function resumed.

Figure 26.5 is a real time intracardiac electrogram from a patient s/p a single chamber device who was found to have pauses on telemetry while being hospitalized for an episode acute renal failure. Event markers revealed evidence of failure to capture. Voltage output was subsequently increased. This maneuver coupled with the resolution of electrolyte abnormalities restored normal pacemaker activity.

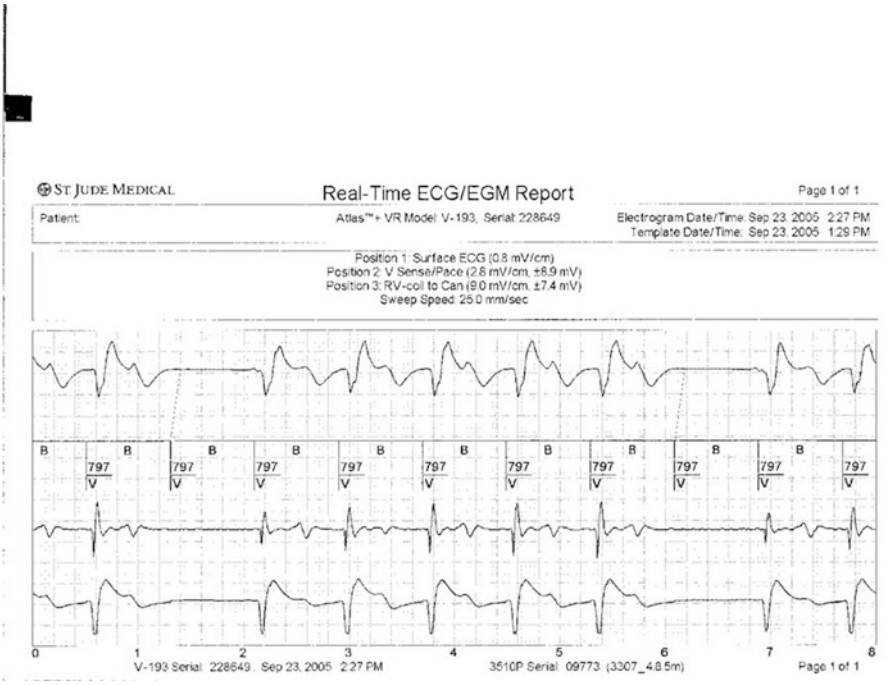

Fig. 26.4 Intermittent ventricular capture

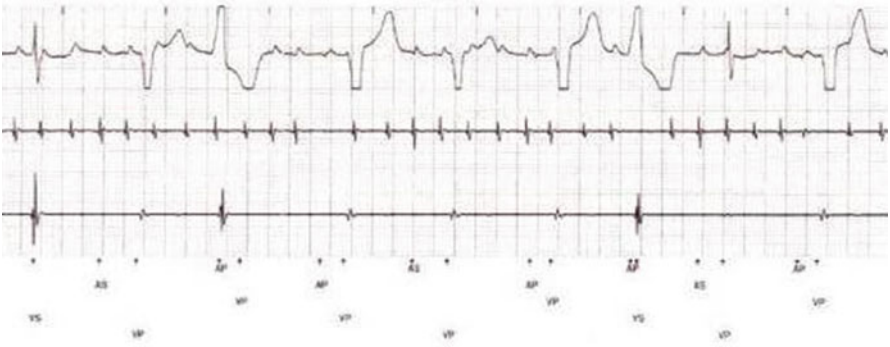

Fig. 26.5 Atrial undersensing: atrial activity is present, but is intermittent on the channel markers at bottom

Clinical Vignettes

Case 1

A 35 year old man with complete AV block, pacemaker dependency, contacts the pacemaker clinic to inform them that earlier in the day he had an unheralded syncopal episode. This resulted in a laceration on his forehead. The day before, he reported two presyncopal spells. He had never had any prior episodes. He is known to have had obstructive hypertrophic cardiomyopathy and left bundle branch block and had undergone alcohol septal ablation 5 years ago. The procedure was followed by the development of complete AV block requiring the implantation of a pacemaker.

Upon interrogation of his pacemaker, the RV pacing threshold was seen to have climbed from 0.7 volts at 0.4 ms. measured 4 weeks ago to 5.2 volts at 0.4 ms. Furthermore, the PM interrogation intermittently registered high right ventricular lead impedances. Pacemaker interrogation does not show that he has had any ventricular arrhythmias. His underlying rhythm is sinus with complete AV block and no escape greater than the lowest pacing rate the pacemaker could be programmed to. Elevation of pacing impedance when coupled with elevation of pacing threshold in a lead that has not been recently implanted, raises the concern for a fractured lead. The unheralded syncopal episode along with the two preceding presyncopal spells, point to a recent fracture. The patient is pacemaker dependent, and was admitted so that a new lead could be implanted. While awaiting lead implantation, the impedance and pacing threshold of the RV lead can be tested in unipolar mode. If the pacing threshold and impedance are within normal in the unipolar mode, a temporary pacemaker can be avoided. This observation points to fracture of the outer coil. In this patient, a chest X-ray demonstrated the fracture.

Case 2

Seven years after a 78-year old hypertensive male patient receives a dual chamber pacemaker for complete AV block he contacts the PM clinic complaining of a 1-week history of fatigue and shortness of breath. Examination reveals an otherwise healthy man with a BP 110/70 mmHg and a pulse 65 bpm. An electrocardiogram demonstrates sinus rhythm, complete AV block and ventricular pacing at 65 bpm in a VVI mode. Given the age of this pacemaker, the battery most likely crossed the elective replacement interval (ERI). Pacemakers are programmed to revert to a mode that would consume less energy, slowing down impending battery depletion, consequently, the shift to the VVI mode. However, upon losing atrioventricular synchrony, symptoms not unlike those of heart failure can be provoked. Once a new, dual chamber PM was implanted, the patient's symptoms were completely relieved.

Suggested Reading

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Chapter 27
Cardioversion and Defibrillation

Aaron E. Brice

Cardioversion and defibrillation are both techniques of terminating cardiac arrhythmias. Direct current (DC) cardioversion uses the discharge of electrical energy through the myocardium to terminate certain arrhythmias. In DC cardioversion shock delivery is synchronized with the QRS complex to avoid provoking ventricular fibrillation (VF). If a shock is given during the vulnerable refractory period of ventricular repolarization, VF may result [1]. In comparison defibrillation uses no synchronization and the shock is given randomly in the cardiac cycle. Monophasic and biphasic waveforms have been shown to be effective in cardioversion and defibrillation. In the use of biphasic waveforms current polarity becomes reversed which more consistently terminates arrhythmias with less energy delivered.

Indications

Cardioversion is effective in eliminating arrhythmias caused by a reentrant circuit by depolarizing all tissue in the circuit and inducing a refractory period which breaks the circuit. Cardioversion is therefore only indicated for specific arrhythmias (Table 27.1). Defibrillation may be employed in cardiopulmonary resuscitation and is indicated for VF, pulseless ventricular tachycardia (VT), and polymorphic VT. In cases of hemodynamic instability, angina, or heart failure caused by tachyarrhythmias immediate shocks are indicated. In the absence of such features cardioversion may be done electively. Appropriate timing of cardioversion, use of vagal maneuvers, and medications including antiarrhythmics are specific for each arrhythmia.

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Table 27.1 Type of arrhythmia and response to cardioversion/defibrillation [1]

Reentrant (shockable)	Ventricular fibrillation Most ventricular tachycardias Atrial fibrillation Atrial flutter AV reentrant tachycardia (AVRT) AV nodal reentrant tachycardia (AVNRT) SA nodal reentrant tachycardia
Automatic (not shockable)	Sinus tachycardia Junctional tachycardia Atrial tachycardia Accelerated idioventricular rhythm

Contraindications

There are few absolute contraindications to cardioversion and defibrillation. Patients with digitalis overdose or electrolyte abnormalities including hypokalemia are at increased risk of developing VF or VT with cardioversion. The procedure should be deferred if possible until these are corrected. Atrial fibrillation of unknown or prolonged duration should not be cardioverted without first taking appropriate steps to reduce risk of thromboembolism. Caution must be taken in patients with severe disease of the cardiac conduction system as a shock may precipitate bradyarrhythmia and temporary pacing capabilities should be on hand. Sinus tachycardia may be a physiologic response to a specific cause such as hypotension and should not be confused with a rhythm treatable with cardioversion.

Patients with implantable cardioverter/defibrillators (ICD) or pacemakers can undergo DC cardioversion but the electric charge may disrupt computer programming or damage the device. If cardioversion is performed interrogation must be completed afterward. Pregnancy also is not a contraindication to cardioversion or defibrillation but fetal heart rate should be monitored during the procedure.

Equipment

External cardioversion and defibrillation normally employ pads or paddles that are pressed to the skin and connected by cables to a case housing the computer, energy source, and cardiac monitor (Fig. 27.1). Devices manufactured prior to 2000 normally use monophasic waveforms and those made after use biphasic waveforms. Electrode types include handheld paddles that use electrically conductive gel and self-adhesive pads which stick to the patient's skin [2].

Equipment for monitoring heart rhythm and vital signs should be available along with supplies needed for an emergency response including a code cart for advanced cardiac life support, temporary pacing, and airway equipment. Supplemental

Fig. 27.1 Portable cardioverter/defibrillator

oxygen should be present. Clippers for removing excess hair may be necessary for application of adhesive pads and to reduce electrical impedance. If procedural sedation is to be performed the appropriate sedative and analgesic agents must be available.

Technique

Intravenous access, cardiac telemetry, and vital signs monitoring must be present throughout the procedure. A 12-lead electrocardiogram should be done prior to and following cardioversion. To reduce the risk of aspiration patients should not eat or drink for at least 6 h before elective cardioversion. Supplemental oxygen should be removed prior to discharge of any electrical energy due to the risk of fire.

Procedural sedation is commonly performed as cardioversion may cause pain, anxiety, and unpleasant memories. Commonly used agents with initial dose in mg/kg include midazolam (0.02–0.03), fentanyl (0.5–1.0), etomidate (0.1–0.15), ketamine (1.0–2.0), and propofol (0.5–1.0).

Proper electrode placement is important for successful cardioversion as this determines the pathway of current [3]. Pads are primarily placed in two positions, antero-lateral and antero-posterior (Fig. 27.2). If an ICD or pacemaker is present pads or paddles should not be placed directly over the device and the antero-posterior position may be favored. Pad placement should also avoid breast tissue.

The initial amount of energy selected will depend on the arrhythmia being treated (Table 27.2). Higher energy levels have greater effectiveness in terminating the arrhythmia but are more likely to result in complications. The lowest energy should be used that is effective in eliminating the abnormal rhythm.

The synchronization function should be selected for cardioversion and the cardiac monitor should be checked to verify the arrhythmia is still present. The

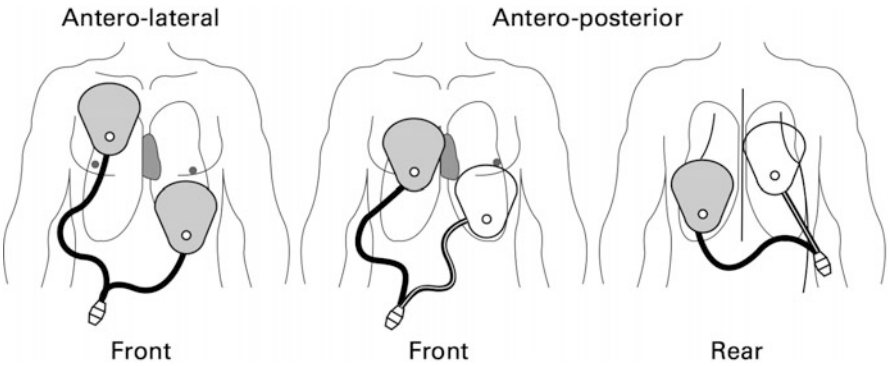

Fig. 27.2 Correct pad placement

Table 27.2 Suggested initial energy for cardioversion/defibrillation [1]

Arrhythmia	Biphasic waveform	Monophasic waveform
Atrial fibrillation	120–200 J	200 J
Atrial flutter	50–100 J	50–100 J
AVNRT, AVRT	50–100 J	50–100 J
Monomorphic VT with pulse	100 J	100 J
Polymorphic VT and pulseless VT	120–200 J	360 J
Ventricular fibrillation	120–200 J	360 J

capacitor may then be charged and all personnel should be cleared and avoid contact with the patient or bed. The clinician may then manually press the button to discharge a shock. The monitor should be checked after shock delivery to verify termination of the arrhythmia. If the arrhythmia is still present the energy level should be escalated in a stepwise fashion and repeat shock delivered with a minimum of 1 minute between shocks.

Data Interpretation

If the device cannot synchronize with the QRS complex the electrical deflections may be too small to capture and the clinician should reposition the pads placing them closer to the patient's heart.

When evaluating the post cardioversion electrocardiogram temporary ST elevations and depressions or T wave changes may be noted. This usually occurs in the absence of cardiac biomarker elevation and is a nonspecific finding rarely due to myocardial injury [4].

Cardiac monitoring commonly displays arrhythmias after cardioversion. Malignant arrhythmias such as VF and sustained VT must be quickly recognized

and treated with defibrillation. Sinus arrest and other bradyarrhythmias may occur but are usually of short duration; if persistent, cardiac pacing may be required.

Complications

Transcutaneous discharge of electrical energy may result in pain and first-degree burns at the site of shock delivery and is related to the amount of energy used. Good contact with the defibrillator pad/paddle and skin is essential. Improper pad placement and use of monophasic waves increase this risk. Cutaneous burns may be best treated with a cream, such as Silvadene. Myocardial necrosis may manifest as a small elevation in cardiac biomarkers. This is usually due to high energy discharge.

Thromboembolism is a risk in patients with atrial fibrillation or atrial flutter treated with cardioversion. Risk is reduced with 4–6 weeks of anticoagulation or transesophageal echocardiogram confirming absence of clot in the left atrium.

Hypotension may be seen after cardioversion and is usually brief and responsive to IV fluids. Pulmonary edema is infrequently encountered and may be due to left ventricular dysfunction or decreased atrial mechanical activity after shock.

Clinical Vignettes

Case 1

A 67-year-old man is brought to the emergency department by his wife for worsening weakness, shortness of breath, and palpitations. He believes his symptoms began about 2 days ago but is not certain. He has diabetes and heart failure with an ejection fraction of 45% measured 4 months ago. His medications are carvedilol, lisinopril, and metformin. On physical exam he is afebrile, blood pressure is 74/52, heart rate is 122, respiratory rate is 32, and oxygen saturation is 82% on face mask. Cardiac exam discloses an irregularly irregular rhythm and on lung auscultation rales can be heard bilaterally. Laboratory studies are pending. Electrocardiogram shows an irregularly irregular narrow complex tachycardia.

This patient has atrial fibrillation with rapid ventricular response that is hemodynamically unstable. Synchronized DC cardioversion should be quickly delivered. He is hypotensive and ventricular rate control with a nondihydropyridine calcium channel blocker or beta blocker should not be attempted. Unlike the present case, an elective transesophageal echocardiogram or prolonged anticoagulation are preferred, when feasible, to reduce the risk of thromboembolism in stable patients with atrial fibrillation for more than 48 hours. However, immediate synchronized cardioversion is indicated in unstable and symptomatic patients.

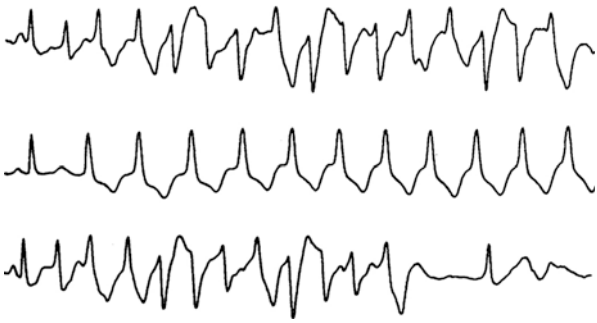

Fig. 27.3 Case 2 cardiac monitor display

Case 2

A 52-year-old woman undergoes elective cardiac catheterization for evaluation of coronary artery disease. No obstructive lesions are found but after the procedure while in the periopertive area she develops chest pain, palpitations, and severe anxiety. On physical exam she is afebrile, blood pressure is 105/72, heart rate is 180, respiratory rate is 22, and oxygen saturation is 96% on room air. She appears nervous and cardiopulmonary exam reveals a rapid heartbeat but is otherwise unremarkable. Serum chemistries are normal. Her cardiac monitor is examined and is shown in Fig. 27.3. Electrocardiogram prior to catheterization shows normal sinus rhythm with QTc interval of 410.

This patient has spontaneous polymorphic VT with a normal QT interval. This may be seen in the setting of structural heart disease, familial syndromes, or coronary artery disease. She currently has stable blood pressure but may decompensate and should be shocked with an unsynchronized defibrillation energy level of 120–200 J. In comparison recommendations for initial energy selection in monomorphic VT with a pulse are 100 J synchronized. Polymorphic VT is classified according to presence or absence of QT prolongation. She does not have polymorphic VT with prolonged QT interval or torsades de pointes which is responsive to magnesium.

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Part IV
Interventional Cardiology

Chapter 28
Coronary Angiography

Nima Aghili, Edouard Daher, and Carey Kimmelstiel

Introduction

Coronary angiography remains the gold standard for evaluation of ischemic heart disease. For more than 50 years, cardiac catheterization and the invasive evaluation of coronary arteries has defined the role of a cardiologist and serves as the diagnostic backdrop for coronary intervention and myocardial revascularization.

Indications

Coronary angiography is performed most commonly after non-invasive tests have shown the presence of coronary artery disease (CAD) in patients presenting with symptoms of chest pain, despite medical therapy. These noninvasive tests could be conclusive as to the presence of CAD, and in that case, angiography is performed to accurately define the coronary arterial anatomy and whether any defined stenoses are suitable for revascularization to achieve symptom relief. In the case of indeterminate non-invasive tests results, coronary angiography is frequently performed

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when the index of suspicion for CAD remains high. Occasionally, patients are referred for coronary angiography in the setting of an emergency such as acute coronary syndromes such as myocardial infarction or unstable angina. Coronary angiography is performed in patients with newly diagnosed cardiomyopathy and in cases of valvular or congenital heart diseases to evaluate for concomitant CAD that might affect the therapeutic management of these patients, especially when surgical correction is planned. Coronary angiography is also indicated in recipients of heart transplant to evaluate for "cardiac allograft vasculopathy" (CAV) which can affect up to 50 % of patients during the first 10 years following transplantation [1].

Contraindications

The only absolute contraindication for performing coronary angiography, is a mentally competent patient that refuses to consent for the procedure. More commonly, there are relative contraindications for this procedure when the risk of coronary angiography outweighs the benefit. These include, but are not limited to uncontrolled hypertension, uncontrolled ventricular arrhythmias, severe electrolyte abnormalities, severe bleeding diathesis, history of contrast intolerance, renal insufficiency, a non-cooperative patient, or one with a febrile condition that has not been treated. These conditions should be assessed carefully against the potential benefit of cardiac catheterization. These issues can mostly be addressed and coronary angiography then performed safely once they are corrected or adequately treated. Of note, a patient that has renal insufficiency but is already contemplating or undergoing dialysis does not have contraindications for proceeding with coronary angiography. Moreover, in cases where coronary angiography is urgent, such as in patients presenting with an acute coronary syndrome, coronary angiography should not be delayed. Instead, efforts should be concentrated on minimizing the risks associated with the relative contraindications, therefore decreasing the risk of complications.

Equipment

The fluoroscope and the hemodynamic monitor are the basic components required to perform a coronary angiogram. Hemodynamic monitoring is performed continuously during the procedure to monitor central and peripheral aortic pressure as well as heart rate and rhythm. The fluoroscope includes an x-ray tube and generator, and the image intensifier (Fig. 28.1). The fluoroscope is mounted on a C-arm that rotates around the patient in a half circle of 180° while the patient is lying supine on the table. Some labs are equipped with dual x-ray tubes and image intensifiers at a 90° angle, so that orthogonal views of the coronary arteries can be imaged simultaneously, thus reducing procedural time as well as minimizing contrast and radiation

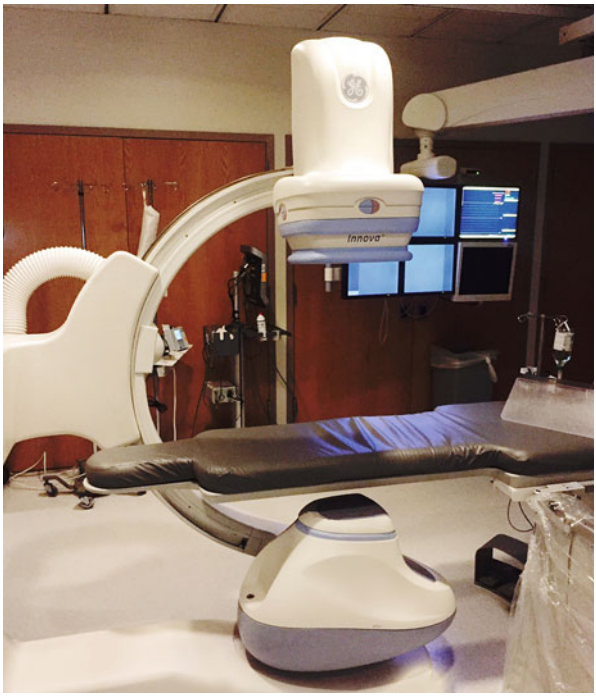

Fig. 28.1 Fluoroscopic unit

exposure to the patient. A contrast power injector is utilized for ventriculography and aortography when these procedures are performed.

Images are captured using equipment that store images in a digital format where they can be displayed off line for further viewing and analysis and where reports are generated. The hemodynamic data acquired during the case are also digitally stored (Fig. 28.2). Disposable equipment come in sterile packaging. These include various supplies such as syringes, needles, wires, manifolds, sutures, clamps, bowls, gauze, drapes, towels, and catheters (Fig. 28.3). A code cart needs to always be present in the angiography suite in the event of an emergency such as a cardiac arrest or a cardiac arrhythmia that requires resuscitation of the patient.

Technique

Coronary angiography is performed via access to the femoral, radial or brachial artery. For the femoral approach, which is still the dominant route utilized in the United States, under sterile conditions, the groin is prepped and local anesthesia is applied. A needle is used to access the femoral artery through which a wire is advanced into the aorta. Fluoroscopy is used briefly to confirm the position of the wire in the aorta and the needle is exchanged over the wire for a sheath, usually 5 or 6 F, which is inserted into the femoral artery where catheter exchanges can then be

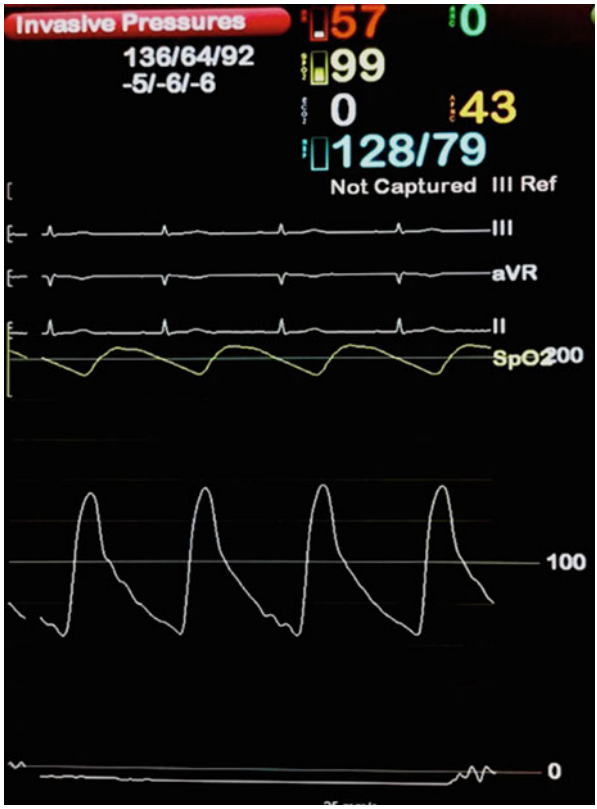

Fig. 28.2 Example of an aortic pressure tracing during a cardiac catheterization

made. The radial approach requires testing the patency of ulnar artery by performing an Allens's test [2] prior to the procedure. This is done, because placement a catheter can result in thrombosis or rarely injury to the radial artery. Therefore the test is used to reduce the risk of hand ischemia ensuring adequate collateral flow from the ulnar artery. The Allen's test is performed by having the patient clench their fist. The, physician then applies occlusive pressure to both the ulnar and radial arteries, to obstruct blood flow to the hand. The patient then opens their hand, and the patient's fingers are observed to ensure that they have blanched. The physician then releases the occlusive pressure on the ulnar artery to determine its patency and adequate perfusion to the hand in the event of radial artery occlusion. Reversal of blanching and return of normal hand coloration or flushing the hand within 5–15 s indicates adequate perfusion of the hand by the ulnar artery allowing for use of the radial approach. Once the radial sheath is inserted a wire is advanced through the sheath to ascending aorta.

Irrespective of the route of arterial access, once the sheath is placed, a preformed catheter (Fig. 28.3) is then advanced over the wire, with fluoroscopy guidance through the sheath into the ascending aorta. A number of different catheters are used to selectively engage the left and right coronary arteries. Once selectively engaged,

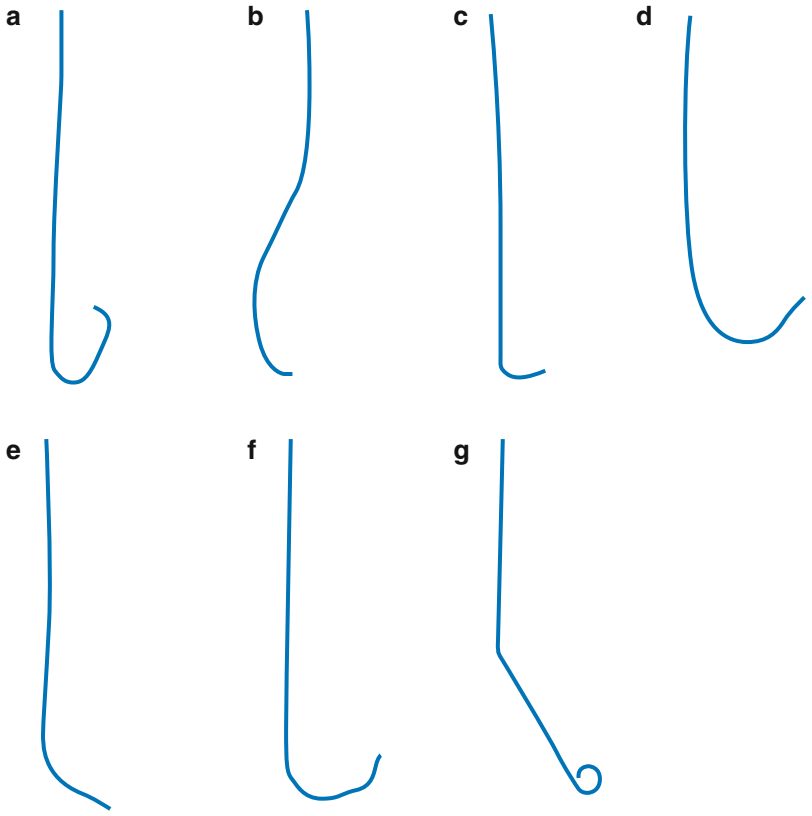

Fig. 28.3 Example of different coronary (**a**–**f**) and left ventricular (**g**) catheters. *A* Judkins left, *B* Judkins right, *C* Modified Amplatz Right, *D* Amplatz Left, *E* Multi-purpose, *F* Jacky, *G* Pigtail

iodinated contrast is injected at a rate of 5–7 cc/s and cineangiography is performed in multiple angulated views with different obliquities to capture the major coronary arteries and their branches in orthogonal views for the detection of coronary stenoses. Frequently, a pigtail catheter is used to perform left ventriculography as well as aortography to assess left ventricular systolic function, the presence and severity of mitral and aortic regurgitation. If a right heart catheterization is being performed at the same time, the assessment of mitral and aortic stenosis can be performed as well. The pigtail catheter is positioned in the proximal aorta, above the coronary arteries when performing aortography and is otherwise advanced across the aortic valve into the left ventricle to perform left ventriculography or perform the hemodynamic assessment of stenotic left sided heart valves. For imaging, the pigtail catheter is connected to a power injector that is programmed to deliver contrast at a specific rate and volume into the aorta or left ventricle. The catheter has several sideholes and the distal end of the catheter is curved – both properties lend themselves to atraumatic contrast delivery while minimizing trauma to the area where it

resides. After all views are obtained, the catheters are withdrawn from the body through the access sheath.

Upon completion of the cardiac catheterization the access sheath is removed. In the case of femoral access cases, frequently, vascular closure devices are used to aid in achieving hemostasis. The totality of the data suggests that these devices might reduce the incidence of bleeding, albeit at a greater financial cost as opposed to not using them. If these devices cannot be deployed, then manual compression is applied for approximately 20 min to provide hemostasis. Patients are then asked to remain supine at bed rest for a period of approximately 4 h. Radial sheaths are removed with the use of compression bands. These bands proved pneumatic compression of the radial artery and are deflated after 1–2 h. Vital signs should be done routinely as part of standard post-procedural care. Special attention should be given to the distal lower extremity pulses where the access was obtained.

Data Interpretation

There are three main coronary arteries (Fig. 28.4). The left main coronary artery takes its origin from the superior portion of the left coronary sinus and then divides into two main branches that usually supply blood to the left ventricle: the left anterior descending artery (LAD) along with its diagonal and septal branches supply the anterior, anterior septal, apical and anterolateral left

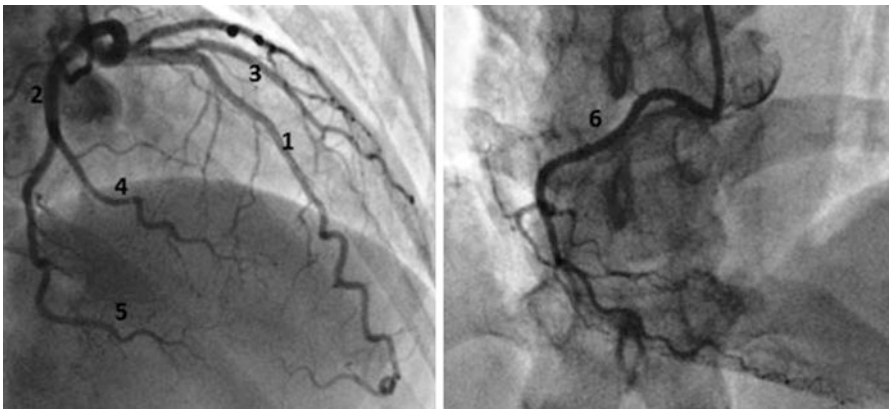

Fig. 28.4 Normal coronary anatomy: *Left image*: Left main bifurcates into Left Anterior Descending artery (*1*) and Left Circumflex (*2*). The LAD gives rise to diagonal branches (*3*) and the LCx gives rise to the obtuse marginal branch (*4*). In approximately 10 % of the population, the posterior descending artery (*5*) arises from the left circumflex artery as opposed to the RCA. *Right image*: Right Coronary Artery (*6*)

ventricular (LV) walls, The left circumflex artery (LCX) along with its obtuse marginal branches supply the lateral LV wall. In 10–15 % of patients, the LCX gives rise to the posterior descending artery (PDA) which supplies blood to the inferior LV wall. The right coronary artery takes its origin from the right aortic sinus and supplies the right ventricle through its RV branches, and usually the inferior and the posterior walls of the LV through the PDA and posterior LV branches respectively.

Coronary angiograms are performed to determine the percent diameter stenosis of coronary arteries. This is done by measuring the diameter of the stenosed vessel and dividing it by diameter of the normal reference reference vessel. Coronary arteries should be imaged in at least two orthogonal views to most accurately gauge stenosis severity. Visual assessment of a stenosis is most commonly done in the laboratory in daily practice and stenoses greater than 70 % are considered significant [3]. However, the decision of which coronary lesion is responsible for a patient's ischemia is not always certain. Therefore, there are other modalities that can be used as adjuncts to coronary angiography which aid in establishing which coronary lesion is significant. These include imaging techniques such as intravascular ultrasound (IVUS) [4] and optical coherence tomography (OCT) [5] or functional assessment with fractional flow reserve (FFR) [6]. FFR measures the pressure ratio across a coronary artery stenosis at maximal hyperemia to determine the likelihood that the stenosis is responsible for an ischemic syndrome.

In the presence of totally occluded vessels or highly stenotic coronary arteries, evaluation of the supply of the distal coronary bed by collaterals (Fig. 28.5) should be done when performing cineangiography. The vessel of origin and degree of collateralization can be used to guide decision making regarding possible revascularization strategies.

The coronary microvasculature is assessed semi-quantitatively by assessing the 'Thrombolysis In Myocardial Infarction' (TIMI) flow in the respective coronary artery. TIMI flow is graded from 0 which is defined as no perfusion to 3 which indicates normal flow which fills the distal coronary bed briskly and completely [7].

Finally, left ventricular function can be quantified visually and quantitatively through power injection of contrast media into the LV on average at 12–15 cc/s for a total of 35–45 cc of contrast media with the pigtail catheter in the LV. Left ventriculography (Fig. 28.6) can be done in two views simultaneously in angiographic suites equipped with biplane capacity. Assessment of the degree of mitral regurgitation is feasible during left ventriculography with its severity graded visually from 1+ to 4+. Similarly, aortography (Fig. 28.7) can be performed to evaluate the severity of aortic insufficiency and for the assessment of structural and congenital heart disease that involves the aorta. Aortography can also be used to locate coronary bypass grafts that have not been seen by selective injection techniques.

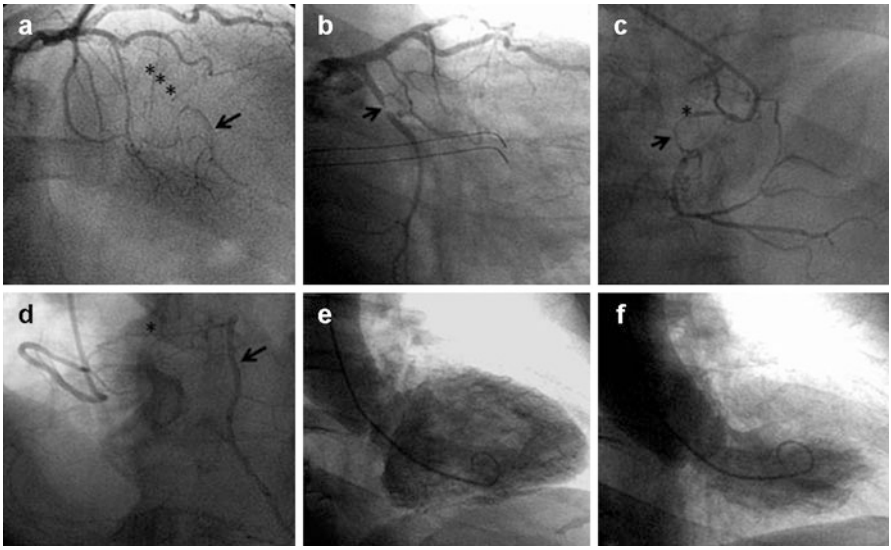

Fig. 28.5 The importance of coronary collateral vessels. (**a**) Site of total occlusion of the LAD (***) which reconstitutes distally (*arrow*) from left-sided collateral vessels. (**b**) The same patient has a significant stenosis of the left circumflex artery (*arrow*). (**c**) The RCA of the same patient is occluded proximally (*star*) and reconstitutes through bridging collaterals (*arrow*). (**d**) The conus branch of the RCA gives rise to collaterals (*) to the occluded LAD (*arrow*). This patient's ventriculography is depicted in diastole (**e**) and systole (**f**) showing an overall normal ejection fraction which is most likely due to the maintenance of myocardial perfusion from collateral blood flow

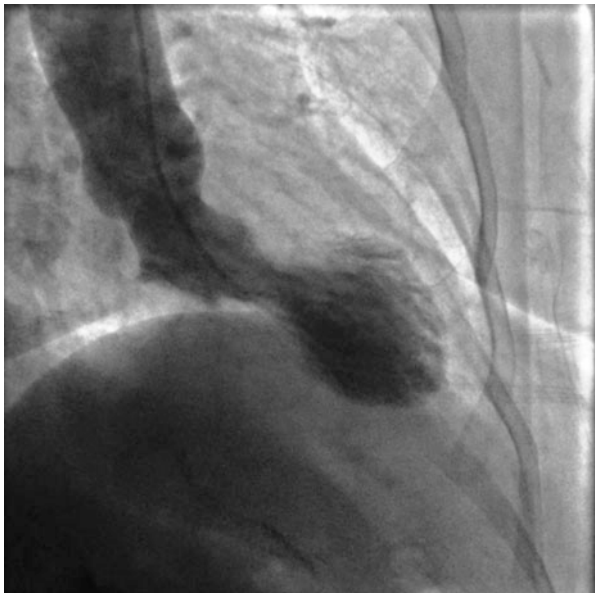

Fig. 28.6 Left ventriculogram in an RAO projection in a patient with stress induced cardiomyopathy showing apical ballooning

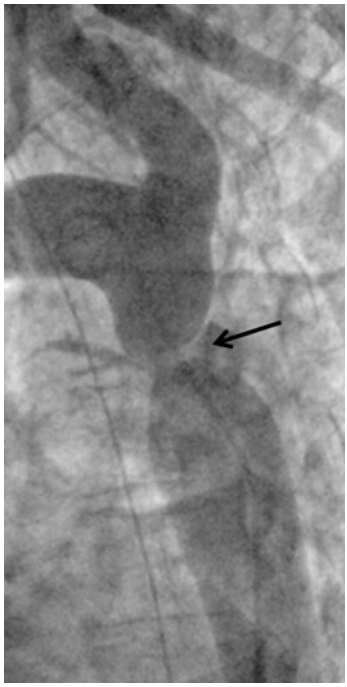

Fig. 28.7 Aortography in a patient with a descending aortic coarctation (*arrow*)

Complications

Coronary angiography is for the most part a relatively safe procedure with a low risk of complications in the average population, however they still do occur. Fortunately, the risk of major complications in current practice is <1 %. The risk varies according to patient characteristics. Patients with an acute coronary syndrome, congestive heart failure, severe vascular disease, left ventricular dysfunction, severe three vessel coronary artery disease, critical valvular heart disease, prior stroke, and history of renal insufficiency are at higher risk for complications compared to other patients. Major complications include the risk of death, myocardial infarction, and stroke which typically occur in <0.5 % of the cases. Other vascular complications including major thrombosis, bleeding requiring transfusion, pseudoaneurysm or arteriovenous fistula occur in <1 % of cases. Minor complications including transient supraventricular arrhythmias, minor bleeding at access sites, fever, and hypotension occur in <3 % of cases. Transient increase in creatinine is believed to occur in at approximately 5 % of patients. Allergic reactions to dye occur in about 1 % of patients. A morbid complication of coronary angiography and heart catheterization is systemic cholesterol embolization that occurs in <0.2 % of cases but has severe consequences such as renal failure and bowel ischemia/infarction.

Clinical Vignettes

Case 1

A 44 year old male with a history of diabetes, hypertension and smoking presented with chest pain at rest. His electrocardiogram revealed ST elevation in the lateral leads. He was emergently referred to the cardiac catheterization laboratory.

Coronary angiography was performed through a radial approach and documented proximal thrombotic occlusion of the LCX (Fig. 28.8). The patient underwent uneventful primary angioplasty and stenting of the occluded LCX and made an uneventful recovery.

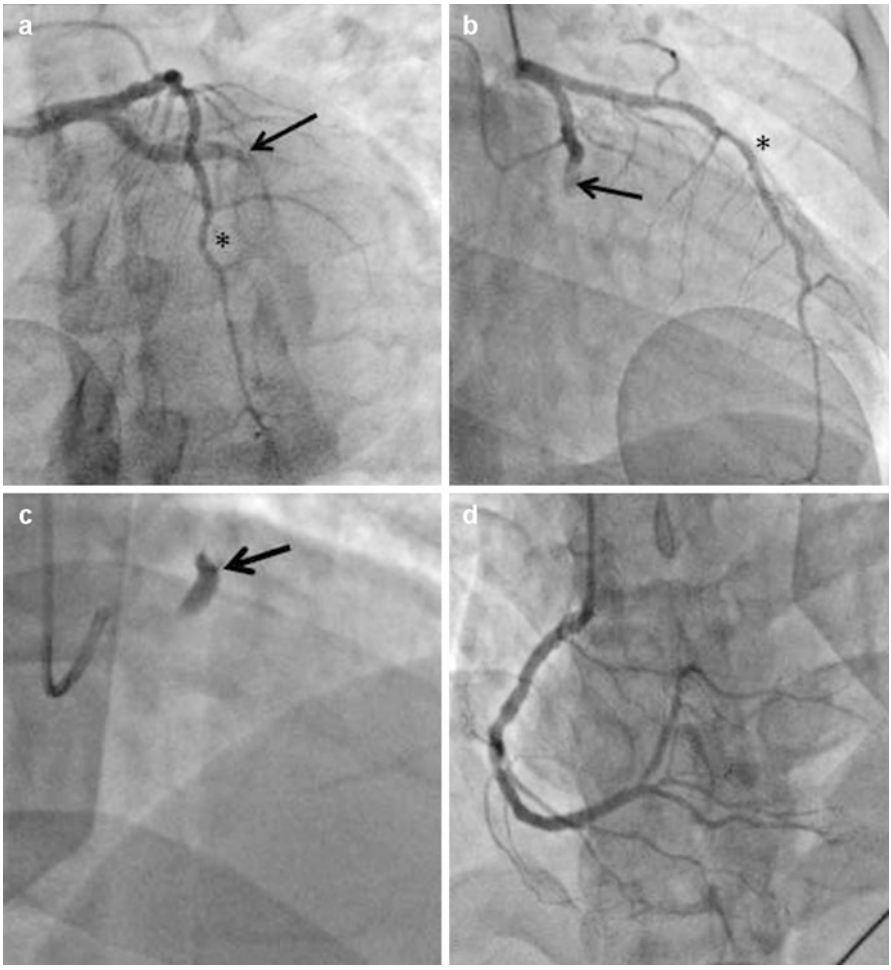

Fig. 28.8 Case 1 catheterization images. (**a**) LAO caudal view shows the LAD (*) and thrombotic occlusion of the LCX (*arrow*); (**b**) AP caudal view also shows the LAD (*) and thrombotic occlusion of the LCX ; (**c**) RAO cranial view before injecting contrast depicts residual staining from prior injection in the LCX due to thrombus; (**d**) LAO cranial view of the RCA

Case 2

A 64 year old man with multiple cardiac risk factors including hypertension, hyperlipidemia, known coronary artery disease, and a previous history of smoking presented with increasing angina which was unsuccessfully treated with multiple anti-anginal medications. He was referred for a stress test that revealed a large infero-lateral ischemic defect.

The coronary angiogram documented a critical stenosis in the mid LCX (Fig. 28.9). The mid LCX lesion was stented with a single drug-eluting stent and the patient was afforded complete relief of his angina.

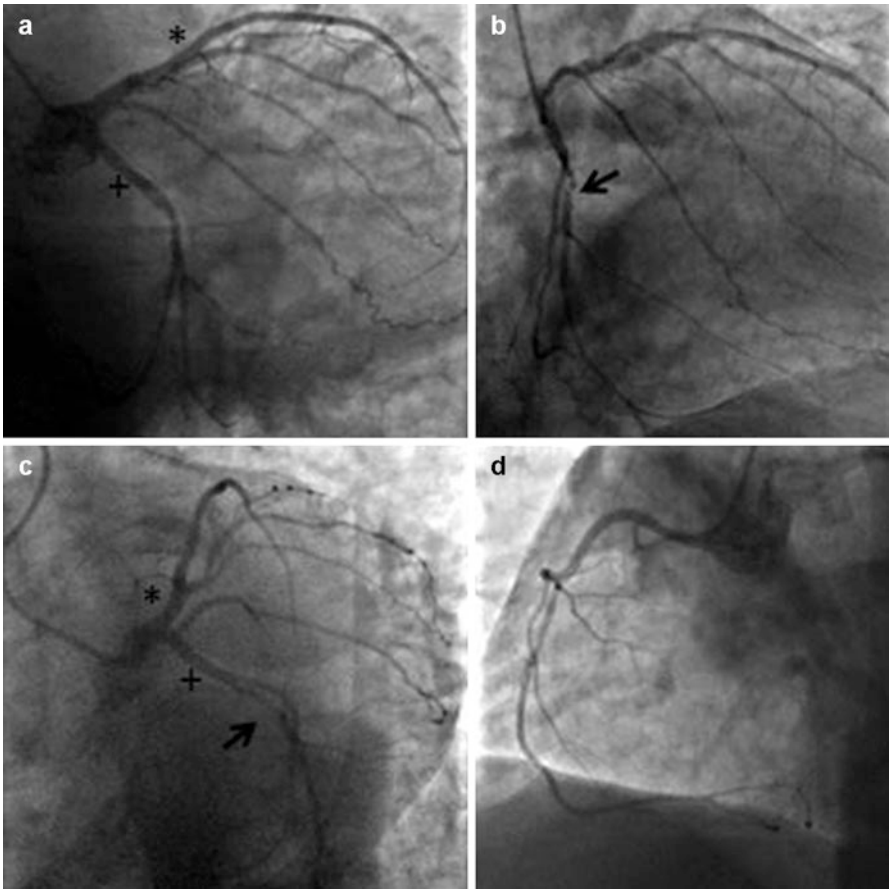

Fig. 28.9 Case 2 angiography. (**a**) AP caudal view showing the LAD (*) and the LCX (+); (**b**) RAO caudal view showing the stenosis in the LCX (*arrow*); (**c**) LAO caudal view also shows the proximal LAD (*) and the LCX (+) with the critically stenotic segment (*arrow*); (**d**) LAO Cranial view of the RCA in this patient

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Chapter 29
Coronary Blood Flow Measurements

Morton J. Kern

Introduction

Measuring coronary blood flow and pressure provides unique information that complements the angiographic evaluation and facilitates decision-making regarding therapy. Precise quantification of stenosis severity by angiography is limited by the inability to provide accurate two or three dimensional resolution on coronary "luminograms". The limitations of coronary angiography have been well documented by comparisons to intravascular ultrasound and ischemic stress testing. Direct measurement of coronary blood flow velocity and distal perfusion pressures allow the interventional cardiologist to have a complete assessment of both coronary anatomy and physiology.

Coronary pressure and flow relationships can identify the ischemic potential of a stenosis (Fig. 29.1). Angiography (upper left) shows geometry of lesion responsible for pressure (P) and flow (Q) reductions associated with ischemia. Two lesions of the same dimension can have markedly different P-Q relationships (lower left). Fractional flow reserve (FFR) is calculated from distal pressure/proximal pressure ratio at maximal hyperemia (upper right). Coronary flow reserve is calculated from ratio of maximal hyperemic average velocity to baseline velocity (lower right).

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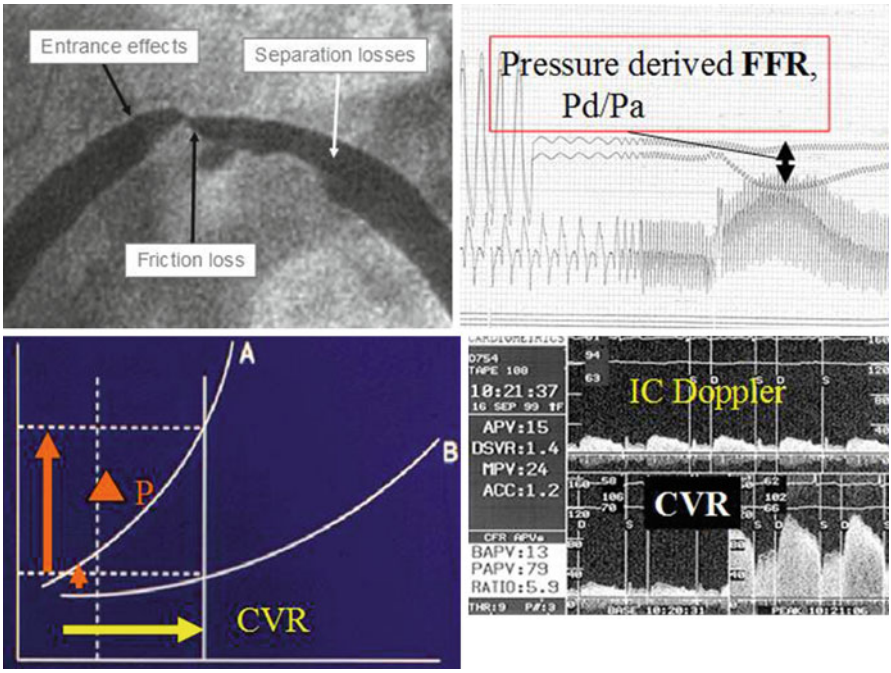

Fig. 29.1 Angiography (*upper left*) shows geometry of lesion responsible for pressure (*P*) and flow (Q) reductions associated with ischemia. Two lesions of the same dimension can have markedly different P-Q relationships (*lower left*). FFR is calculated from distal pressure/proximal pressure ratio at maximal hyperemia (*upper right*). Coronary flow reserve is calculated from ratio of maximal hyperemic average velocity to baseline velocity (*lower right*)

The hemodynamic significance of a given stenosis, as determined by the pressure-flow relationship, can be measured and incorporated into clinical discussion using sensor angioplasty guidewires. A hemodynamically significant coronary lesion is associated with one or more of the following parameters which have been correlated to provokable myocardial ischemia:

1. For Coronary Doppler,
   (a) Poststenotic absolute coronary flow reserve (CVR) <2.0
   (b) Relative coronary flow reserve (rCVR) <0.8
   (c) Proximal to distal flow velocity ratio (P/D) <1.7
   (d) Diastolic to systolic velocity ratio (DSVR) <1.8
2. For Coronary pressure, the hyperemic translesional pressure ratio, also known as the FFR has a treat/no treat threshold of <0.80 to treat for best outcomes. An ischemic threshold of <0.75 has a 90 % sensitivity and 90 % specificity for correspondence to stress testing [1]

Indications

Indications for performing coronary physiologic measurements include those lesion subsets whose clinical relevance is uncertain following angiography. These include intermediate severity stenosis, assessment of culprit lesions in patients with multivessel coronary artery disease and guiding therapy in patients with tandem lesions or diffuse disease in an epicardial vessel. Coronary physiologic studies are useful in areas poorly studied angiographically eg. ostia and bifurcations, and can also be used to assess prognosis following stent implantation. Coronary physiologic testing is useful in assessing ischemic potential of patients with prior myocardial infarction (MI), in patients with treated unstable coronary syndromes and to assess the collateral circulation. Table 29.1 summarizes the indications for using coronary physiologic measurements.

Contraindications

The contraindications to physiologic measurements are few. According to current guidelines, no physiologic measurement (FFR/CVR) is needed for clinical decisions when the clinical, angiographic and objective ischemia markers are concordant for

Table 29.1 Indications for physiologic measurements in the catheterization laboratory

Coronary pressure measurements
1. Assessment of Intermediate stenosis in one or more coronary arteries (including left main)
2. In patients with multivessel disease, determination of one or more target stenoses (either serially or in separate vessels)
3. Evaluation of ostial or distal left main and ostial right lesions, especially when these regions can not be well visualized by angiography
4. Guidance of treatment of serial stenoses in a coronary artery
5. Determination of significance of focal treatable region in vessel with diffuse coronary artery disease
6. Determination of prognosis after stent deployment
7. Assessment of stenosis in patients with previous (non-acute) myocardial infarction
8. Assessment of lesions in patient with treated unstable angina pectoris
9. Assessment of the collateral circulation
(NOTE: For STEMI, not useful for acute IRA lesion assessment <6 days after MI)
Coronary Doppler flow
1. Assessment of Microcirculation
2. Endothelial function testing
3. Myocardial viability in acute myocardial infarction
Combined coronary pressure and Doppler flow velocity
1. Assessment of intermediate stenosis
2. Assessment of the microcirculation

the diagnosis. Other contraindications include the inability to use anticoagulation for angioplasty sensor wire placement, unstable clinical syndromes (relative contraindication) and unsatisfactory hemodynamic recording equipment [2].

Equipment

Intracoronary physiologic measurements are made with standard angioplasty equipment and techniques. Doppler flow velocity can be measured using a Doppler-tipped angioplasty guidewire. This guidewire is a 175 cm long, 0.014 in. diameter, flexible, steerable wire with a piezoelectric ultrasound transducer integrated into the tip (FloWire; Volcano Therapeutics, Del Mar, CA)

Several companies make pressure wire/catheter products. Unique handling characteristics arise from special construction of the device. Current pressure wire sensors are either piezo-electric or optical. Pressure wires also differ from regular workhorse wires having to incorporate the thin wires or optical fibers that transmit the pressure signals (Fig. 29.2).

Technique

After diagnostic angiography or during angioplasty, the sensor guidewire is passed through an angioplasty Y-connector attached to a diagnostic or guiding catheter. (Note: Side holes in large diameter guiding catheters have been used to alleviate catheter related partial obstruction of the coronary ostium. Side hole guiding catheters required an approximate doubling of the intracoronary (IC) adenosine dose due to loss of drug from the side holes during instillation.) Intravenous (IV) heparin 40–70 units/kg and IC nitroglycerin (100–200 μg) are given several minutes before the guidewire is advanced into the artery.

For flow velocity, the sensor tip is advanced at least 5–10 artery-diameter lengths (>2 cm) beyond the stenosis to measure velocity in a region of re-established laminar flow. Resting flow velocity data are recorded. Induction of coronary hyperemia by IC or IV adenosine is performed, continuously recording through peak hyperemic flow velocity. Coronary flow velocity reserve, CFVR is computed as maximal hyperemic to basal average peak velocity (APV). Poor Doppler signal acquisition may occur in 10–15 % of patients even within normal arteries. Like transthoracic echo Doppler studies, the operator must adjust the guidewire position (sample volume) to optimize the velocity signal [3].

For translesional pressure (FFR) measurements, the wire pressure is first matched to the guide catheter pressure in the central aortic location, and then the wire is advanced into the artery beyond the stenosis. Baseline pressure is recorded, followed by induction of coronary hyperemia with IC or IV adenosine, continuously recording both guide catheter and sensor-wire pressures. FFR is computed $\text{Pressure}_{\text{distal}}/\text{Pressure}_{\text{aorta}}$ at maximal hyperemia. $\text{Pressure}_{\text{distal}}$ is recorded from the pressure wire,

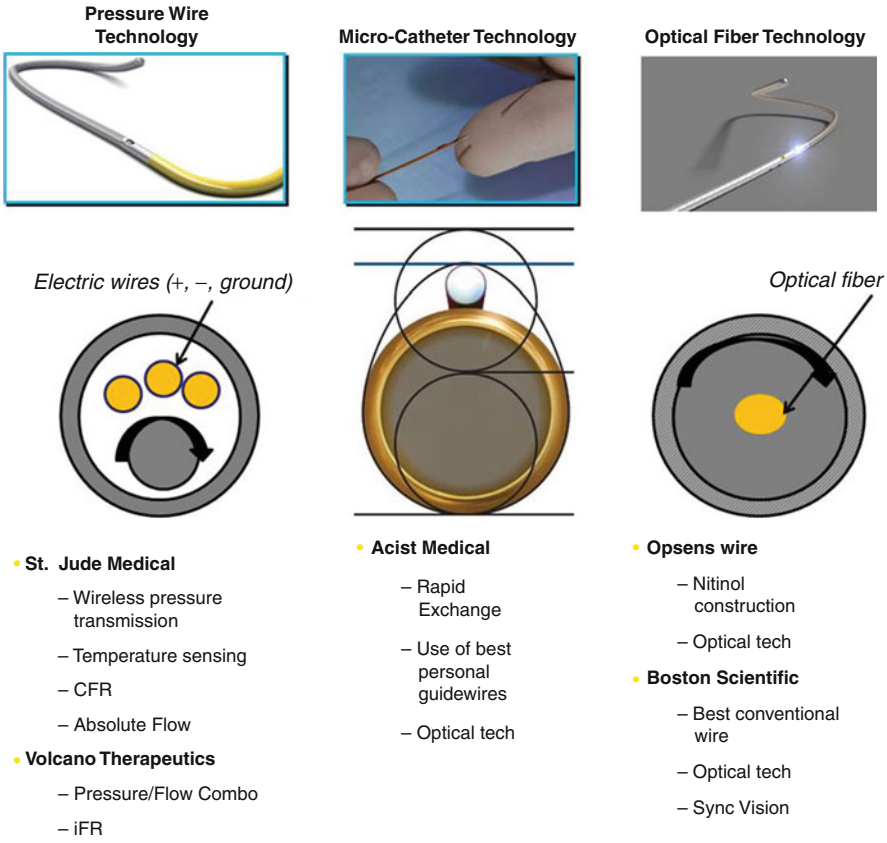

Fig. 29.2 Comparisons of available pressure wires. Sensor Wire/Catheter Construction and special features of current pressure wire and microcatheters systems for FFR. *Left* standard wire core surrounded by thin transmission and ground wires for piezo-resistive transducer signal. *Center* shape of Rxi microcatheter. *Right* nitinol or cobalt *chromium* wire core around central optical fiber to transmit pressure signal. Increase in core dimension and concentricity produces increase torque. Piezo-electric wires have core wire (*Steel*, *Thin*, *low torque*) compared to optical wires with hollow wire (nitinol or Cobalt Chromium, larger, high torque. From Kern MJ. Cath Lab Digest, May 2016)

$\text{Pressure}_{\text{aorta}}$ is recorded from the guide catheter that delivers the pressure wire. Pressure signal artifacts may be reduced by careful attention to technique.

Stenosis severity should always be assessed using measurements obtained during maximal hyperemia. Adenosine is the most common agent for hyperemia. It has a short half-life, with a return to basal flow within 30–60 s after cessation of infusion. IV and IC adenosine are very well tolerated with ~10 % drop in mean arterial pressure but may be accompanied by short lived symptoms of dyspnea or chest burning. Although transient, AV block may rarely occur at higher IC doses in the RCA. IV adenosine uses weight-adjusted dosing (140 mcg/kg/min), and is required for the evaluation of ostial lesions or for the assessment of diffuse disease during pullback recordings. Compared to IC, IV administration has a higher incidence of side effects

such as flushing, chest tightness, bronchospasm, nausea, and transient AV block or bradycardia. IC adenosine doses that produced maximal hyperemia equivalent to IV adenosine are 50–100 mcg for the right coronary artery, 100–200 mcg for the left coronary artery produces [4].

Alternative to adenosine includes Regadenson, an α2A adenosine receptor agonist that induces coronary vasodilatation and increased myocardial blood flow in a manner reportedly equivalent to adenosine with fewer adverse effects and IC nitroprusside. Regadenoson has a half-life of 2–3 min in the initial phase, 30 min in the intermediate phase and 2 h in the terminal phase. It is administered as single intravenous bolus (0.4 mg), and thus may be easier to use, but its cost and prolonged effect may complicate the measurement of multiple lesions or arteries [5].

IC nitroprusside can be an alternative to IC adenosine. Serial doses of IC nitroprusside (boluses of 0.3, 0.6, and 0.9 mcg/kg) [6] produced equivalent coronary hyperemia with a longer duration (about 25 %) compared with IC adenosine. IC nitroprusside (0.9 mcg/kg) decreased systolic blood pressure by 20 % with minimal change in heart rate, whereas IC adenosine had no effect on these parameters. IC nitroprusside, in doses commonly used for the treatment of the no-reflow phenomenon, can produce coronary hyperemia suitable to measure FFR without detrimental systemic hemodynamics.

A summary of pharmacologic hyperemic agents for cath lab measurements is provided in Table 29.2.

Data Interpretation

Ischemic Thresholds of Coronary Physiologic Measurements

An FFR of <0.75 identified coronary stenoses in patients with inducible myocardial ischemia, with high sensitivity (88 %), specificity (100 %), positive predicted value (100 %), and overall accuracy (93 %). An CFR of <2.0 corresponded to reversible myocardial perfusion imaging defects with high sensitivity (86–92 %), specificity (89–100 %), predictive accuracy (89–96 %), and positive and negative predictive values (84–100 % and 77–95 %), respectively [7, 8].

Multivessel Coronary Artery Disease

Data from multiple recent clinical trials [9–11] strongly support the concept that patients with multivessel CAD benefit from appropriately guided physiologic guided revascularization with an FFR >0.80 associated with exceptionally good prognosis treated with optimal medical therapy alone. FFR in and around the gray zone important prognostic value, especially in proximal lesions and confirm that FFR ≤0.80 is valid to guide clinical decision making [10].

Table 29.2 Hyperemic agents used for coronary physiology assessment

Agent	Route	Dose	Comments
Adenosine	IV infusion	140 μg/kg per min	Reference standard. Side effects include dyspnea and chest pain. Prolonged hyperemia allows pressure wire pullback
Adenosine	IC bolus	>100 μg	Easy to use, inexpensive, no significant side effects. Transient heart block at high doses. Hyperemia lasts only 10–15 s
Adenosine	IC infusion	240–360 μg/min	Inconvenient set-up. Fewer side effects compared with IV infusion. Prolonged hyperemia allows pullback. Not well-validated
Regadenoson	IV bolus	400 μg	Convenient, single IV bolus. Expensive. Side effects similar to IV adenosine but less severe and briefer. Hyperemia lasts 20 s–10 min
Papaverine	IC bolus	10–20 mg	Easy to use, inexpensive. Rare, but significant side effect of polymorphic VT. Hyperemia lasts 30 s, allowing pullback
Nitroprusside	IC bolus	0.3–0.9 μg/kg	Easy to use, inexpensive. Major side effect is hypotension. Hyperemia lasts 50 s allowing pullback. Not well-validated
Dobutamine	IV infusion	50 μg/kg/min	Inconvenient as it takes time for onset on offset. Side effects includes palpitations and hypotenstion. Not well-validated
Nicorandil	IC bolus	2 mg	Not available in United States. Fewer side effects compared with IV adenosine. Hyperemia lasts 30 s. Not well-validated

From Fearon [12]
FFR indicates fractional flow reserve, *IC* intracoronary, *IV* intravenous, and *VT* ventricular tachycardia

Left Main Coronary Artery Assessment

Numerous studies support FFR use for assessment of left main (LM) coronary stenoses (Table 29.3). For complex LM disease with downstream significant LAD or CFX stenosis, the data from in vitro, animal, and human studies of LM stenosis demonstrate that in most cases, downstream disease does not have a clinically significant impact on the assessment of FFR across an intermediate LM stenosis. Downstream stenoses in the LAD or LCx have to be both severe (i.e. FFR <0.60) and proximal to have a marked effect on the LM FFR. In these situations, IVUS assessment of the LM with a threshold minimal luminal area of <6.0 mm^2 is recommended [13].

Acute Myocardial Infarction

Acute myocardial injury produces transient microvascular dysfunction to various degrees and impairs maximal coronary hyperemia depending on the reduction of myocardial mass, reducing the flow across a stenosis. After the patient

Table 29.3 Left main revascularization outcomes and FFR

First author (Ref. #)	N					Overall survival	
	Total	Defer group	Surgical group	FFR cut off value	FU (months) mean duration	Defer group (%)	Surgical group (%)
Bech et al. [14]	54	24	30	0.75	29 ± 15	100	97
Jasti et al. [15]	51	37	14	0.75	25 ± 11	100	100
Jiménez-Navarro et al. [16]	27	20	7	0.75	26 ± 12	100	86
Legutko et al. [17]	38	20	18	0.75	24 ± 12	100	89
Suemaru et al. [18]	15	8	7	0.75	33 ± 10	100	100
Lindstaedt et al. [19]	51	24	27	0.75	29 ± 16	100	81
Hamilos et al. [20]	213	138	75	0.80	35 ± 12	90	85
Total or (mean)	449	271	178	–	(28 ± 13)	(95)*	(89)

From Puri et al. [13]
FFR fractional flow reserve, *FU* duration of follow-up, *ULMCA* un protected left main coronary artery
*p = NS compared with surgical group

recuperates, myocardial recovery may increase coronary flow, and higher flow would lower the FFR, perhaps below the ischemic threshold thus changing a treatment decision from that made during the acute event. As a result FFR of a vessel (i.e. a lesion different from the culprit lesion, but in the same vessel) that is involved in a ST-elevation myocardial infarction or large non-NSTEMI can result in a false-negative result. FFR has been demonstrated to be accurate after 4–6 days, and in most unstable angina patients and small NSTEMI patients. FFR of most non-culprit lesions at a distance from the infarct related artery, has also been shown to be accurate. Trials that have evaluated the use of FFR in ACS are summarized in Table 29.4.

Complications

The complications of coronary physiologic measurements are the same as those related to diagnostic coronary angiography and less than those associated with coronary angioplasty. The major safety considerations are those involving guiding catheter/wire vessel trauma (not different from regular angioplasty wires), thrombus, or coronary vasospasm. The incidence of such complications are <0.01 %. The use of vasodilators, such as adenosine, may be associated with bradycardia and

Table 29.4 FFR and ACS trials

			Author	N	
Acute MI	Culprit vessel	Unreliable	Tamita 2002	33 STEMI	Mean FFR after successful PCI was higher (0.95 ± 0.04) than in ref group of stable angina patients (0.90 ± 0.04, p = 0.002) despite identical IVUS paramaters, likely reflecting microvascular stunning & dysfunction
Acute MI	Non-culprit vessel	Reliable	Ntalianis 2010	75 STEMI, 26 NSTEMI	112 non-culprit lesions measured acutely and 35 ± 24 days later. Only 2 lesions had clinically meaningful change – FFR >0.80 during the acute episode and <0.75 at follow-up
Recent MI	Culprit vessel	Reliable	De Bruyne 2001	57 Acute MI with viable myocardium on LVgram	FFR after acute MI (≥6 days, mean 20 days) compared to SPECT before and after PCI. FFR <0.75 had high sensitivity (87 %) and specificity (100 %) for detecting ischemia on true positive/negative SPECT. BCV for FFR 0.78. Inverse correlation between FFR and LVEF – for a similar degree of stenosis, FFR depends on mass of viable myocardium
Recent MI	Culprit vessel	Reliable	Samady 2006	36 STEMI, 12 NSTEMI	FFR after acute MI (STEMI ≥3 days, NSTEMI ≥2 days, mean 3.7 days) compared to SPECT at 11 weeks. FFR ≤0.75 had high sensitivity (88 %), specificity (93 %), and overall accuracy (91 %) for detecting reversibility on true positive/negative SPECT. BCV for FFR 0.78
Recent MI	Non-culprit vessel	FFR-guided PCI = good clinical outcomes	Potvin 2006	125 ACS, 60 SIHD, 16 Atypical CP	201 consecutive pts (62 % unstable angina, NSTEMI, or >24 h after STEMI) with ~50 % stenosis in which PCI was deferred based on FFR ≥0.75. No difference in clinical outcomes between ACS and stable angina pts
Recent MI		FFR-guided PCI = good clinical outcomes	Fischer 2006	35 ACS	FFR-guided PCI of intermediate lesions (50–70 %). Deferring PCI for FFR ≥0.75 in pts with recent ACS. Similar MACE rates at 12 months compared to pts without ACS
UA/ NSTEMI	Culprit vessel	FFR-guided PCI = good clinical outcomes	Leesar 2003	70 UA/ NSTEMI	Recent NSTE-ACS with intermediate single-vessel lesion randomized to immediate FFR-guided PCI vs. post-angio SPECT. FFR-guided treatment reduced hospital stay & cost, with no increase in procedure time, radiation exposure, or clinical event rates at 1 year
UA/ NSTEMI	Culprit + Non-Culprit vessel	FFR-guided PCI = good clinical outcomes	Tonino 2011	326 UA/ NSTEMI	FAME study. FFR-guided PCI vs. angiography-guided PCI for multivessel disease. In subset of pts with recent NSTE-ACS, significantly lower MACE rate with FFR-guided PCI

hypotension. Overall, the clinical practice using sensor wire measurements with pharmacologically induced hyperemia is safe with the benefit of valuable information off setting the small risk of the invasive approach.

Clinical Vignettes

Case #1

69-year-old man with exertional angina presents for evaluation. Chest pain was substernal, radiated to the neck and left shoulder. It was relieved with rest and recently responded to sublingual nitroglycerin. *An exercise radionuclide perfusion imaging study was positive for anterior reversible defects. Coronary angiography was performed and showed a LAD and OM1 lesion (Fig. 29.3a, top; white arrow and *, respectively). Because of anterior ischemia on stress testing, angioplasty and stent placement was performed in the LAD (Fig. 29. 3b, top). For interest, FFR in the LAD was 0.56 before angioplasty (Fig. 29.3a, bottom) and 0.94 after stent placement (Fig. 29.4b, bottom).*

The operator now approached the OM1 lesion. (fig, top (*)) The clinical options included medical management, stent placement or FFR assessment and management accordingly. Because there was no demonstrable ischemia, the operator elected to perform FFR and provide a definite assessment of the ischemic potential of the lesion. A sensor wire pull back was performed (Fig. 29.4) and indicated an FFR of 0.86 and pull back pressure gradually increasing to 0.96 over the course of the vessel. Medical Management was then instituted with annual follow-up.

Case #2

72-year-old woman with atypical chest pain occurring at rest and with exertion. No stress testing was performed. Coronary angiography was performed and demonstrated normal coronary arteriography with the exception of ostial left main narrowing in one angiographic projection only (Fig. 29.5, arrow). The options for management from this point forward included patient referral for immediate bypass surgery,, perform FFR and/or IVUS while in the catheterization laboratory or discharge the patient from the catheterization laboratory and refer for in-patient stress testing.

FFR was performed with intravenous infusion of adenosine (140 mcg/kg × 4 min) and was abnormal at 0.68. IVUS also demonstrated a lesion cross-sectional area of 3.9 mm2 relative to a reference vessel area of 9.8 mm2 (Fig 29.5, right side). The patient was referred for coronary bypass surgery.

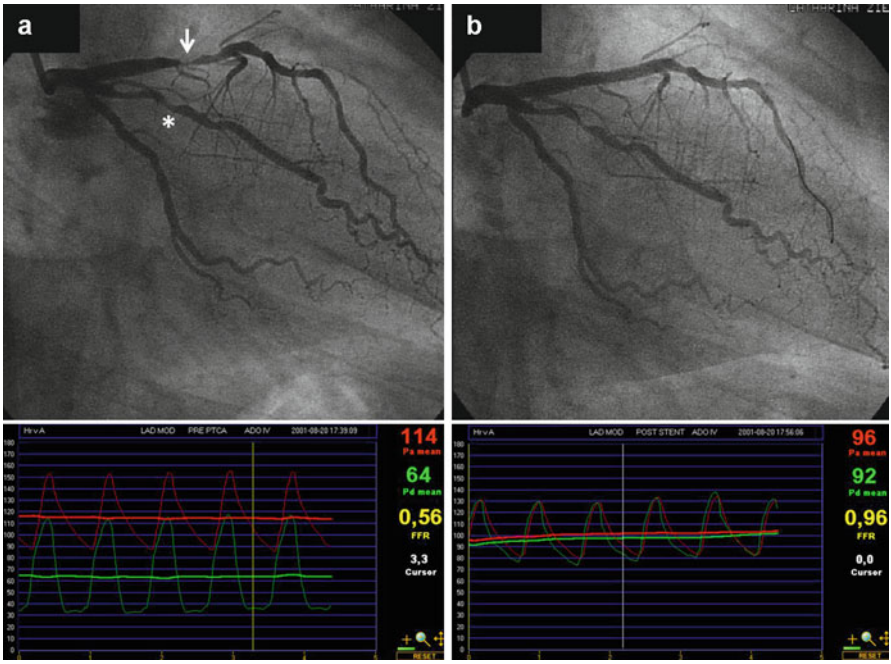

Fig. 29.3 (**a**) *Top* – Coronary angiogram showing lesions in the LAD (*arrow*) and first obtuse marginal branch of the left circumflex artery (*). *Bottom* – FFR across the LAD lesion. (**b**) *Top*. Angiogram showing the stented LAD. *Bottom* – FFR in the LAD following stenting

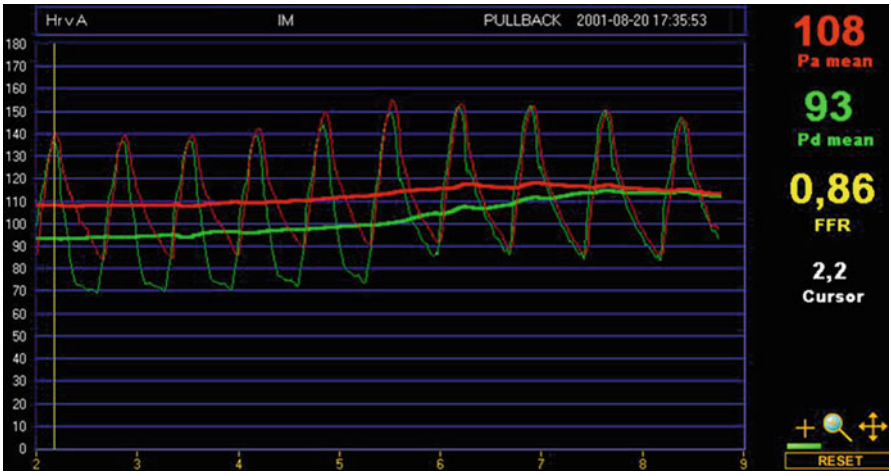

Fig. 29.4 Pull back FFR of the obtuse marginal lesion shown in figure 4, starting distally and moving proximal to the lesion. The FFR distally of 0.86 is shown in the figure

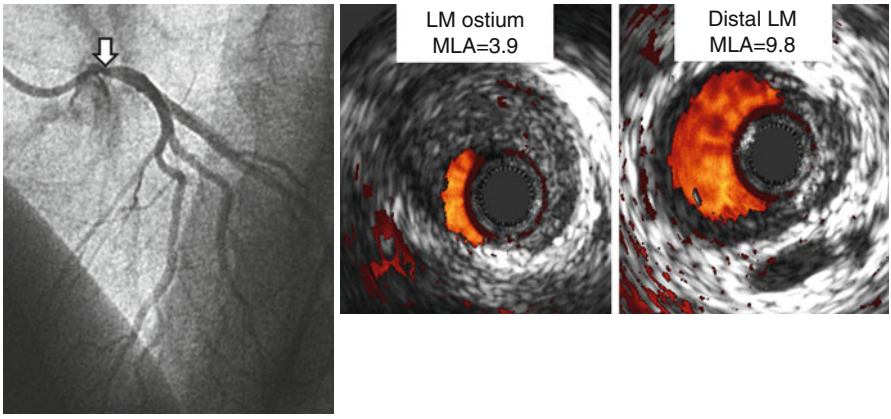

Fig. 29.5 *Left side* – Coronary angiogram showing an eccentric left main lesion (*arrow*). *Right side* – Intravascular ultrasound imaging of the ostium of the left main and the distal reference vessel

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Chapter 30
Percutaneous Coronary Intervention

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Introduction

There are over one million percutaneous coronary interventions (PCI) performed each year in the United States. PCI refers to catheter- based procedures that allow for improved perfusion through epicardial coronary arteries to the myocardium. PCI originally referred to percutaneous transluminal coronary angioplasty, a solely balloon-based procedure, but has since expanded to include directional, rotational, orbital and extraction atherectomy, excimer laser angioplasty, and most commonly, stent deployment. The devices used for PCI are meant to relieve coronary stenoses by several mechanisms including fracturing or debulking the atherosclerotic plaque and stretching the target arterial segment. PCI is successful in reducing fatal and nonfatal ischemic complications in patients with acute myocardial infarction and high-risk acute coronary syndromes.

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Indications

PCI is indicated in patients whose clinical presentation is an acute coronary syndrome including ST segment elevation myocardial infarction, non-ST segment elevation myocardial infarction, and unstable angina. It is also indicated in those patients with angina pectoris and objective evidence of ischemia with one or more high-grade coronary artery lesions who have failed medical therapy. PCI is also indicated in patients who have a high burden of ischemia on stress testing with favorable anatomy [1]. Several invasive tools are available to further assess angiographically moderate stenoses. Fractional flow reserve (FFR) is a measurement that can be obtained using a coronary pressure wire comparing pressure distal and proximal to a stenosis during maximal hyperemia with an agent such as adenosine. An FFR value less than 0.8 would be an indication to intervene. Intravascular ultrasound is useful in further defining coronary anatomy and characterizing the plaque burden and morphology, eg. the presence of calcification as well as quantitating the luminal area which can be useful in selecting which devices and which size devices to be used in PCI. A luminal area of less than 4 mm^2 in the left anterior descending, left circumflex or right coronary arteries is one indication to perform PCI. In the left main coronary artery, a luminal area of less than 6 mm^2 is considered indicative of significant disease.

Contraindications

Contraindications to PCI can be divided into those related to patient characteristics and those related to coronary anatomy. Patient factors such as a history of recent gastrointestinal bleeding, intracranial hemorrhage, recent surgery or bleeding diathesis are relative contraindications. Active life threatening bleeding is an absolute contraindication to PCI. Coronary revascularization should not be performed in asymptomatic patients with <50 % stenosis severity without evidence of ischemia on objective testing which in the current era often involves FFR determination. Coronary artery anatomy may also predict the feasibility and success of PCI in a certain patient. Coronary calcification, severe tortuosity, small reference vessel diameter (<1.5 mm), and diffuse disease are all characteristics that may predict poor outcomes with PCI. Consequently, a careful evaluation of lesion and patient characteristics should be performed prior to embarking on PCI. In complex cases, a multidisciplinary team approach is indicated to determine the best management strategy for the patient (PCI versus coronary artery bypass grafting versus medical therapy) [1, 2].

Equipment

Access

In order to perform a PCI the procedural planning and required equipment depends upon access. Femoral, brachial and radial arteries are all potential access points for intervention based on the operator's preference and the patient characteristics. Routine access is usually a 6 French sheath via the right radial or right femoral artery. However, complex anatomy such as bifurcation lesions or heavily calcified lesions may require a 7 French sheath and femoral access for guide catheter support to more easily perform PCI with potentially higher-profile devices.

Guiding Catheter

Guiding catheters have larger inner lumen diameters than diagnostic catheters and allow for the passage of guidewires, balloon catheters, and stents into the coronary artery and across the lesion. These catheters are selected based on the size of the ascending aorta, coaxial engagement of the coronary artery and the amount of backup support required to perform the case safely and effectively. The most commonly used catheters are the Judkins left and right coronary guiding catheters. Guiding catheters can be divided into active or passive manipulation catheters. The Judkins left and Ikari left are active-type catheters, meaning a power position can be employed by the operator to provide backup support. The Extra back up (EBU) and Xtra backup (XB) are passive-type guides which provide support without the need for operator manipulation. These may be easier to use but are associated with a somewhat higher risk of left main dissection. For the right coronary artery, the Ikari left can be used from the radial approach as an active-type guiding catheter. The Amplatz left is a passive-type guiding catheter (Fig. 30.1).

Guidewires

Guidewires are usually 0.014 in-thickness wires that are advanced across a lesion in the coronary artery and used as a rail to support the passage of devices. The guidewires are selected based on coronary anatomy and lesion morphology. Each guidewire must be flexible, steerable, as well as stiff enough to support advancing devices past the lesion. Guidewires are characterized by their coating, their stiffness, and tip load. When compared to hydrophobic wires, hydrophilic wires allow for easier passage across lesions but increase the risk of entering the subintimal space and small

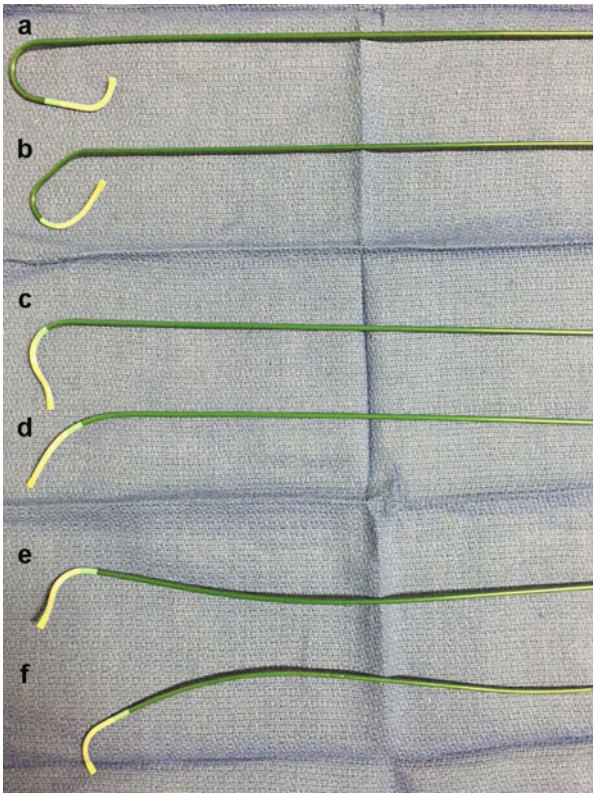

Fig. 30.1 This image shows six guiding catheters. (**a**) A JL-4 guiding catheter is used to engage the left coronary artery and obtain images of the left coronary system in different projections. (**b**) A Voda Left-3 catheter is used to engage the left coronary artery. It is particularly useful for providing enhanced support for LCx coronary interventions. (**c**) An Amplatz Left-1 catheter is a supportive guide which can be used to engage the left coronary arteries and bypass grafts and occasionally, the native right coronary artery. (**d**) A multipurpose-1 catheter can be shaped in the body and used to engage any coronary or bypass graft. It is particularly useful for anomalous coronary arteries. (**e**) An Amplatz Right 2 guiding catheter is useful in engaging the native right coronary artery as well as anomalous right coronary arteries with an inferior take-off. (**f**) A JR-4 diagnostic catheter is used to engage the right coronary artery and obtain images of the right coronary artery in different projections. This catheter can also be used to engage bypass grafts

branches. An operator usually has a "workhorse" wire, which is a safe wire that is used routinely. A workhorse wire should be safe, durable, retain its tip shape, have 1:1 torquability, and offer moderate support for the delivery of devices. If the operator is unable to succeed using the workhorse wire, a different wire is used. The next choice of wire depends on the specific barrier to success with the workhorse. If more support is needed, upgrading to a wire with extra support such as a Choice Extra Support, Grand Slam or HT Iron Man is recommended. If there is difficulty in crossing the lesion, one may consider using a hydrophilic wire but these wires are more likely to enter the subintimal space and are associated with a modestly higher

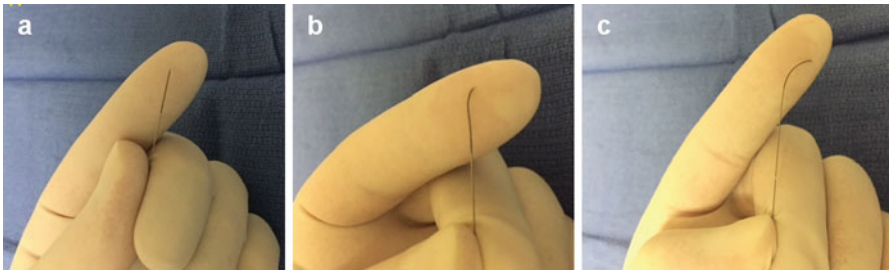

Fig. 30.2 This is an image of a coronary wire. In (**a**–**c**) one can visualize different curves on the wire to allow for access to the desired vessel. Wires are shaped based on the size and tortuosity of the vessel and the angle at which the target vessel comes off the main branch

risk of perforation. If the difficulty is crossing the lesion because of insufficient tip load in the case of a chronic total occlusion, one may move to a specialty wire such as a Miraclebros 3–12 or a Confianza Pro 9–12 (Fig. 30.2).

Balloon Catheters

Balloon catheters are meant to perform lesion dilatation. When selecting a balloon, the operator must decide on the diameter, length and compliance of the balloon. An ideal balloon to artery ratio of 0.9–1.1 is needed to minimize the risk of dissection and abrupt closure. There are three types of balloon catheters: over-the-wire, monorail, and fixed wire balloon catheters.

Over-the-wire balloon catheters have a central lumen for the guidewire and another lumen to allow for balloon inflation throughout the catheter. This system has the advantage of maintaining coronary artery access with the guidewire distal to the lesion while exchanging balloon and stent catheters. Guidewires can also be exchanged without losing arterial access by pushing the balloon to the distal portion of the artery. Because of the length of the two balloon lumens, additional personnel are needed to aid in exchange of the catheters and guidewires.

The rapid-exchange or monorail balloon catheters have a short segment that contains two lumens. One lumen, which runs the length of the catheter, is used for balloon inflation, while the second lumen is shorter and contains the guidewire. This creates a lower profile catheter and allows a single operator to exchange catheters while maintaining distal wire protection. It also allows for the use of a shorter coronary guidewire. These catheters however require more manipulation of the guidewires and balloon catheters by the operator.

The fixed-wire angioplasty balloon catheters have a balloon mounted on a central hollow wire. The guidewire and the balloon cannot be advanced independently of each other. The chief limitation of this catheter is that the balloon or wire cannot be exchanged without losing access to the vessel. These devices are no longer used.

Stents

Stents are balloon-expandable scaffolds made of stainless steel or alloys and are placed within the lesion. As with coronary balloons, stents are available in over-the-wire or monorail designs. Stents are also selected based on their diameter and length. Stents can be 'bare-metal' without a drug coating or 'drug-eluting,' that is, coated with a medication that prevents neointimal hyperplasia with consequent restensois. The first drug eluting stent (DES) was approved by the FDA in 2003 and currently there are four generations of DES. Although drug-eluting stents decrease neointimal hyperplasia, or restenosis, they have historically required a longer duration of dual antiplatelet therapy because of the increased risk of late stent thrombosis. This increase in late stent thrombosis, has been markedly mitigated with design changes in later generation DES. Bioresorbable or bioabsorbable stents are novel products now widely available in Europe, with one FDA-approved device in which the polymer which delivers the drug is resorbed over several months. The hallmark of these stents is that they are completely resorbed over time and this might conceivably counter some of the perceived limitations of durable metallic stents. These limitations include late stent thrombosis, the need for longer-term dual antiplatelet therapy, the metal scaffold interfering with vascular remodeling and coronary vasomotion and also making future surgical coronary artery bypass grafting (CABG) procedures more difficult [3–5].

Technique

Once a stenosis is identified, careful analysis of the clinical characteristics and coronary anatomy is necessary to determine whether or not the patient would be best served by percutaneous revascularization, CABG or medical therapy. A lesion classification system has been developed to categorize the anatomic risk of the lesion undergoing intervention and is related to the likelihood of a successful procedure (Table 30.1). A relatively newer scoring system called the Syntax score is used specifically to compare outcomes of PCI versus CABG surgery in multivessel disease. Patients with a low Syntax score <22 do equally well with PCI whereas those with a high Syntax score >34 tend to perform better with CABG surgery [1, 2].

After the decision to proceed with an intervention is made, a guiding catheter is introduced through an arterial sheath, typically placed in the femoral, radial, or brachial artery. The guiding catheter is then advanced into the aorta and the coronary artery is cannulated so that the catheter is coaxial to the ostium of the coronary artery. Guiding catheters have distinct shapes and are selected based on their ability to provide adequate backup support for advancing equipment into the coronary artery relative to its take-off from the aorta.

Before advancing guidewires into the coronary arteries, the patient should be started on an intravenous anticoagulation regimen. In general, the adequacy of procedural anticoagulation ia guided by the activated clotting time (ACT) which should be usually be >300 s with the use of IV heparin. The ACT has limited utility

Table 30.1 Classification system describing lesion characteristics related to the likelihood of a successful PCI

Low risk	Moderate risk	High risk
Discrete (length <10 mm)	Tubular (length 10–20 mm)	Diffuse (length >20 mm)
Concentric	Eccentric	Total occlusions >3 months old and/or bridging collaterals
Non-angulated segment (<45°)	Moderately angulated segment (45–90°)	Extremely angulated segments (>90°)
Non-tortuous	Moderate tortuosity	Excessive tortuosity
Little or no calcification	Moderate calcification	Heavy calcification
No major side branch involvement	Bifurcation lesions requiring double guidewires	Inability to protect major side branches
Little or no calcification	Moderate calcification	Heavy calcification
Absence of thrombus	Some thrombus is present	Degenerated vein grafts with friable lesions
Not ostial in location	Ostial in location	

in guiding PCIs in which the direct thrombin inhibitor bivalirudin is utilized. All PCIs require the administration of antiplatelet therapy as post procedural stent thrombosis is disproportionately influenced by platelet functions. Most usually, dual antiplatelet therapy with aspirin and an ADP receptor antagonist (eg. clopidogrel, prasugrel, ticagrelor) are administered at the time of PCI and for 1 year, or even longer in selected patients. A 0.014 in. guidewire is placed in the catheter via a Y-connector (Tuohy-Borst or Copilot) and is maneuvered past the stenosis under fluoroscopic guidance. The guidewire is advanced as far distally into the vessel as needed to support balloon advancement.

Once the lesion is crossed with the guidewire, the balloon catheter is advanced, using the guidewire, as a rail to the target lesion. The balloon is then inflated at the stenosis thereby dilating the lesion. Contrast is then injected through the guide catheter to assess the result of predilation and coronary blood flow. The balloon can be used at this time to help assess, the length of stent required.

A stent is then advanced through the guiding catheter to the target lesion. The stent is deployed at a pressure that will maximize stent expansion within the lesion without causing vascular dissection at the margins of the stent or the much less common complication of perforation. The stent catheter is then removed following stent implantation in the artery. The stent is visualized through a contrast injection to determine if it is properly deployed. Although direct stenting without balloon predilation can be performed, not all lesions are amenable to this technique. Lesions which are calcified and tortuous may prevent optimal stent implantation and should be predilated with a balloon catheter. Intravascular ultrasound can also be used to verify adequate deployment of the stent by visualizing the relationship of the stent struts to the vessel wall. If the stent does not appear to be fully expanded, a non-compliant balloon may then be advanced into the stent and inflated to fully expand it and better appose the stent against the arterial wall.

Several lesion types represent higher-risk anatomic subsets for intervention and require specific techniques to help ensure optimal procedural and clinical results.

Bifurcation Lesions

Bifurcation lesions usually refer to a diseased arterial segment which involves a parent and sidebranch vessel. PCI in these cases should be approached prudently in order to preserve the parent vessel and side branch. If the side branch is a large diameter vessel and there is critical disease within the proximal vessel, then bifurcation stenting should be strongly considered. When the side branch is free of or minimally diseased, provisional stenting is preferable. This refers to the situation when the parent vessel is stented across the origin of the side branch. The side branch is only rewired for ballooning or stenting if there is reduced flow or if the patient has ischemic symptoms referable to flow obstruction in the side branch. If bifurcation stenting is going to be performed, several approaches have been described and the choice of which approach is employed is based on the angle between the side branch and parent vessel as well as other factors.

Saphenous Vein Graft Intervention

Another challenging lesion subset for PCI are those in degenerated saphenous vein bypass grafts. These lesions are at elevated risk of distal embolization into the native coronary vasculature during balloon and stent inflation and can cause no reflow phenomenon – the occurrence of impedance to blood flow to ischemic tissue following the relief of coronary occlusion, presumably due to microvascular obstruction. Due to the high thrombotic burden present in the diseased graft, a distal protection device (Guardwire, Filterwire, etc) should be used, when feasible, to prevent or decrease any downstream debris embolization. The distal protection device is then retrieved and can be assessed for the presence of debris. Intracoronary medications such as nitroprusside and verapamil can also be delivered prophylactically in an effort to prevent no reflow and potentially as a treatment should it occur.

Calcified Lesions

Severe calcified stenoses are associated with decreased success rates and increased risk of complications such as dissection with balloon inflation. Techniques such as rotational atherectomy can debulk the calcified lesion through the use of a high speed (150,000 rpm) diamond tip burr. Orbital atherectomy is a newer technology which is also effective in pretreating calcified lesions to allow for easier delivery of balloons and stents. Orbital atherectomy is contraindicated however for aorto-ostial lesions. These devices debulk calcium, thereby enhancing vascular compliance allowing the diseased segment to be stented.

For patients undergoing high risk PCI with compromised left ventricular function, ongoing ischemia, or in cardiogenic shock, the operator should consider the

implantation of a mechanical support device such as an intra-aortic balloon pump or an Impella.

Once a satisfactory revascularization result is achieved, the artery is imaged in several views demonstrating the result. The guidewire is then removed. A coronary angiogram after wire removal should be performed to ensure there is no distal perforation and to assess vascular anatomy without wire-induced straightening artifacts. The guide catheter is then removed and the arterial sheath should then be removed and hemostasis achieved either via manual compression or with the aid of a vascular closure device.

Post PCI, the patient should be monitored for recurrent myocardial ischemia until discharge. All patients should be made to understand the importance of adhering to recommended medical therapies, including anti-platelet therapies and risk factor modification proven to reduce morbidity and mortality form coronary artery disease.

Data Interpretation

Angiographic success after percutaneous coronary intervention is defined as decreasing the stenosis diameter reduction to <20 % with TIMI-3 flow. Additionally there should be clinical signs of success with relief of signs and symptoms of myocardial ischemia post procedure.

Complications

Acute vessel closure is an important complication of percutaneous coronary intervention and can be caused by dissection, thrombus formation, and spasm. If the target vessel remains closed, then the impaired blood flow can result in hypotension, myocardial infarction, arrhythmia and death. With the advent of coronary stenting and adjunctive pharmacologic therapy, the incidence of acute closure has markedly decreased.

Increased mortality of percutaneous coronary interventions has been associated with advanced age, female gender, diabetes, prior myocardial infarction, multivessel disease and a large area of myocardium at risk. The combined risk of death, nonfatal myocardial infarction, stroke, and emergent bypass surgery during PCI is approximately 1 %.

The most common complication for patients undergoing PCI, however, is bleeding at the arterial puncture site. This may occur in 1–3 % of all cases. Radial access for PCI has been associated with a lower incidence of vascular complications and there are some reports of decreased mortality when radial approach is used for STEMI patients. Moreover, patients with renal insufficiency may develop worsening renal function secondary to the use of iodinated contrast.

Restenosis has been a major determinant of event free survival following coronary intervention and results from elastic recoil and neointimal hyperplasia of the artery. Clinical factors such as diabetes, unstable angina, history of prior restenosis and procedural factors such as smaller minimal lumen diameter and smaller acute gain of the target vessel are predictors of restenosis. With the advent of the antiproliferative drug eluting stents, the incidence of in-stent restenosis has substantially decreased.

Clinical Vignettes

Case 1

A 60 year old female with Type II diabetes presented to the emergency room with 1 h of chest pain radiating to the jaw and left arm. ECG demonstrated ST elevation in leads II, III, and avF. The patient was given aspirin, lopressor, IV Heparin.

The patient was taken emergently to the cardiac catheterization lab and was found to have a 100 % occlusion in the right coronary artery (Fig. 30.3). A JR 4 guiding catheter was placed in the ostium of the right coronary artery and a guidewire was advanced through the target lesion. The lesion was dilated with a balloon (2.0 × 12 mm). A drug eluting stent (3.25 × 20 mm) was then deployed. Angiography demonstrated 0 % residual stenosis (Fig. 30.4).

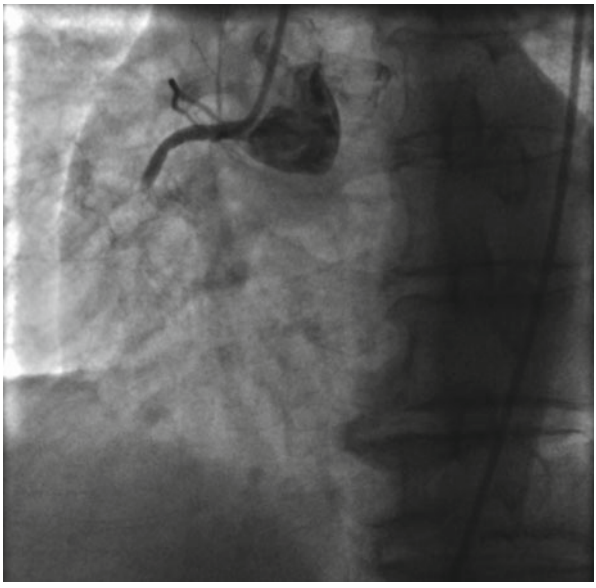

Fig. 30.3 This is a view of the right coronary artery in a left anterior oblique projection which shows a completely occluded mid RCA

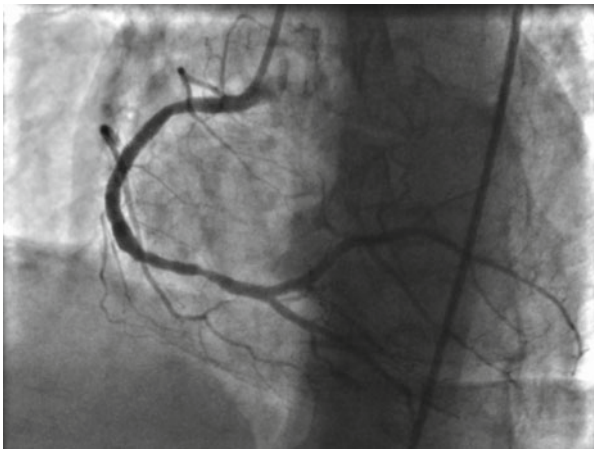

Fig. 30.4 This is an LAO projection of the revascularized RCA

Case 2

A 55 year old male smoker with dyslipidemia presents for an outpatient cardiac catheterization for worsening chest pain with exertion. The patient exercised for 7 min on the Bruce protocol, developed angina with 2 mm ST depression in the precordial ECG leads with a large moderately reversible anterior defect with nuclear imaging.

Angiography revealed a significant stenosis at the LAD/Diagonal bifurcation with a 90 % mid left anterior descending coronary artery lesion and a 95 % Diagonal coronary artery lesion (Fig. 30.5). A balloon catheter (2.0×12 mm) was advanced

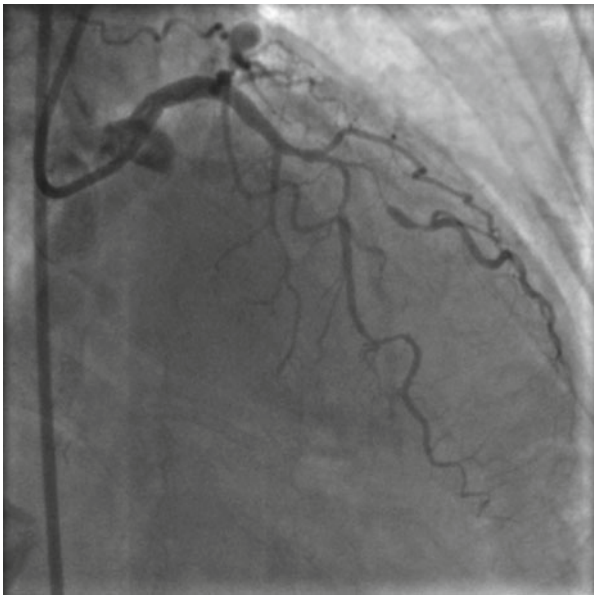

Fig. 30.5 This is an RAO cranial projection of the left coronary system. Once can see that there is a lesion involving the LAD and Diagonal coronary arteries with an 90 % stenosis in the LAD and 95 % stenosis in the diagonal branch

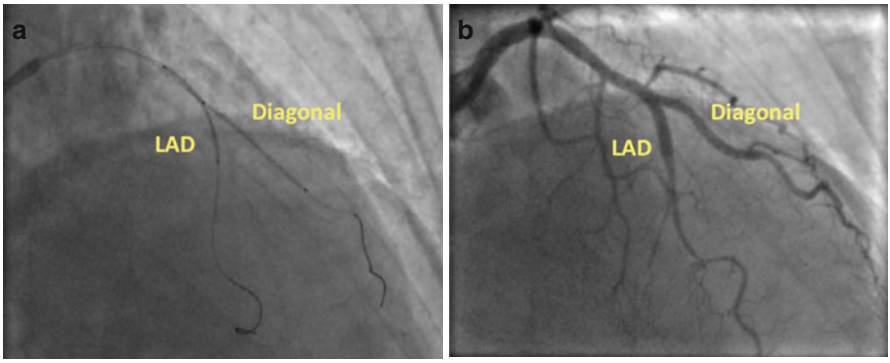

Fig. 30.6 This demonstrates the bifurcation stenting during and after revascularization. A mini-crash technique was used. (**a**) A stent is positioned in the diagonal and a second stent placed in the LAD. The diagonal stent is deployed and the balloon and wire are withdrawn. Next the LAD stent is fully deployed. After that the diagonal branch is rewired and kissing balloon inflation is performed. (**b**) The final result after post dilation

over a guidewire and was inflated at both lesions. A crush technique was used to treat the lesions with a 2.5 × 20 DES to the Diagonal branch and 3.0 × 24 DES to the LAD (Fig. 30.6).

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Chapter 31
Alcohol Septal Ablation

Carey Kimmelstiel

Indications

Hypertrophic obstructive cardiomyopathy (HOCM) is a relatively common genetic disorder that exhibits wide variability in its clinical expression. Symptomatic patients most frequently experience exertional dyspnea, chest pain, fatigue and, occasionally, orthopnea or nocturnal dyspnea. Five to 10 % of symptomatic patients with HOCM are refractory to medical therapy (typically beta blockers and heart rate lowering calcium antagonists) and may require mechanical approaches targeting relief of obstruction and mitral regurgitation. Previously, mechanical approaches were limited to surgical myectomy, however, since the late 1990s increasing experience with a percutaneous technique, alcohol septal ablation, has become a widely-used alternative to surgical myectomy.

General indications for alcohol septal ablation include patients with severe symptoms – New York Heart Association class III or IV, refractory to maximal drug therapy with a left ventricular outflow gradient ≥ approximately 50 mmHg at rest or after provocation, with a basal septal thickness ≥17 mm as measured with echocardiography or MRI [1].

Contraindications

Relative contraindications to performing alcohol septal ablation include coexistent abnormalities that are best treated surgically – eg. multivessel coronary artery disease and especially mitral valve or papillary muscle/mitral apparatus abnormalities

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that contribute to mitral regurgitation and/or left ventricular outflow tract obstruction. These patients, who comprise approximately one-third of the HOCM medication-refractory population, should be referred for surgical myectomy, at which time, coexisting abnormalities can be addressed.

Equipment

Alcohol septal ablation uses standard coronary intervention equipment (Fig. 31.1): a coronary guide catheter, guide wire and angioplasty balloon along with a pulmonary artery catheter to measure pulmonary pressures and an end-hole pigtail or halo catheter to measure the left ventricular pressure. Comparison of the left ventricular pressure to the central aortic pressure determines the left ventricular outflow gradient. All patients have a temporary pacemaker placed at the right ventricular apex. Transthoracic echocardiography is used in all cases to guide ablation.

Technique

Alcohol septal ablation is performed in the cardiac catheterization laboratory. A right and left heart catheterization are performed at which time pulmonary capillary wedge and pulmonary arterial pressures are measured. Left ventricular outflow gradients are measured, usually with an endhole pigtail or halo catheter so as to be able

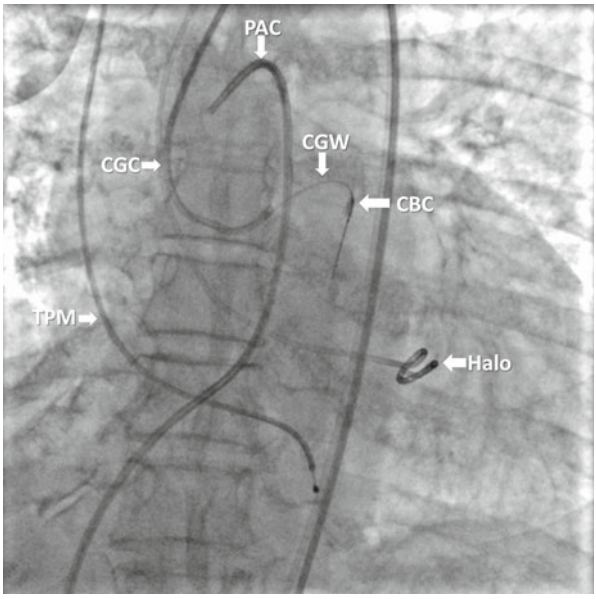

Fig. 31.1 Equipment/catheters used in alcohol septal ablation. *TPM* temporary pacemaker, *CGC* coronary guide catheter, *PAC* pulmonary artery catheter, *CGW* coronary guide wire, *CBC* coronary balloon catheter, *Halo* Halo left ventricular catheter

to record pressure at a precise location within the left ventricle with a catheter whose shape makes entrapment unlikely. Determination of the left ventricular outflow gradient is accomplished by comparing the left ventricular pressure to the central aortic pressure as recorded usually from the coronary guide catheter (Fig. 31.2). It is important to establish the gradient that will be followed to judge procedural efficacy and to establish, with the aid of echocardiography, that the location of obstruction to left ventricular outflow is subaortic. For those patients in whom the outflow gradient is either absent or small at rest, the magnitude of provocable obstruction is most appropriately determined with exercise. If exercise is not feasible, Valsalva maneuver or post-PVC beats are employed.

Prior to proceeding with alcohol infusion, all patients have a temporary pacemaker placed in the apex of the right ventricle as a precaution against the occurrence of complete heart block following alcohol injection. This is usually placed from the right internal jugular vein, as this is a stable route allowing for maintenance of proper positioning following the procedure.

Coronary angiography is performed to assess for the presence or absence of atherosclerotic epicardial coronary artery disease and to identify potential target septal perforator branches, which most often originate from the left anterior descending (LAD) coronary artery. Most practitioners employ myocardial contrast echocardiography, which involves two dimensional echocardiographic imaging during the infusion of 1–2 mL of echo or angiographic contrast through the lumen of an inflated balloon dilatation catheter. This technique enhances the efficacy and safety of the procedure by avoiding septal branches that supply areas of myocardium distant to the targeted region, limiting the number of vessels intervened on, thereby reducing the amount of alcohol used which aids in preventing the complication of complete atrioventricular

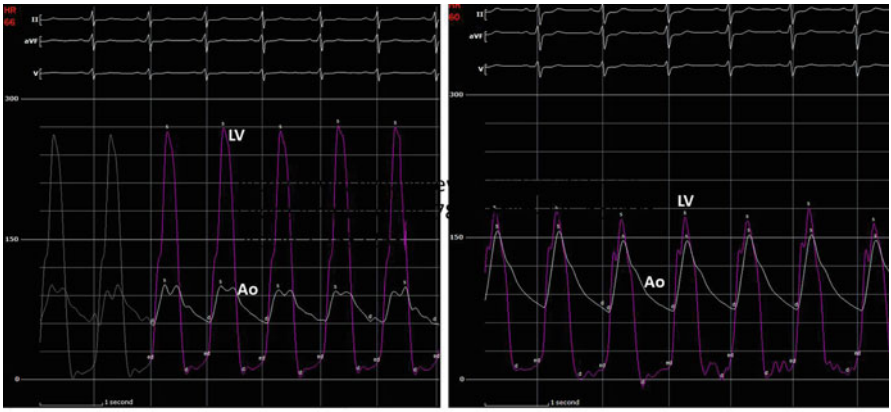

Fig. 31.2 Left ventricular outflow gradients before and following alcohol septal ablation. Before ablation, the gradient is 170 mmHg. Note the bifid aortic waveform, highly suggestive of dynamic outflow obstruction with a narrow pulse pressure. Following ablation, the gradient has been reduced to 20 mmHg. The aortic waveform no longer exhibits a bifid contour and the pulse pressure has increased

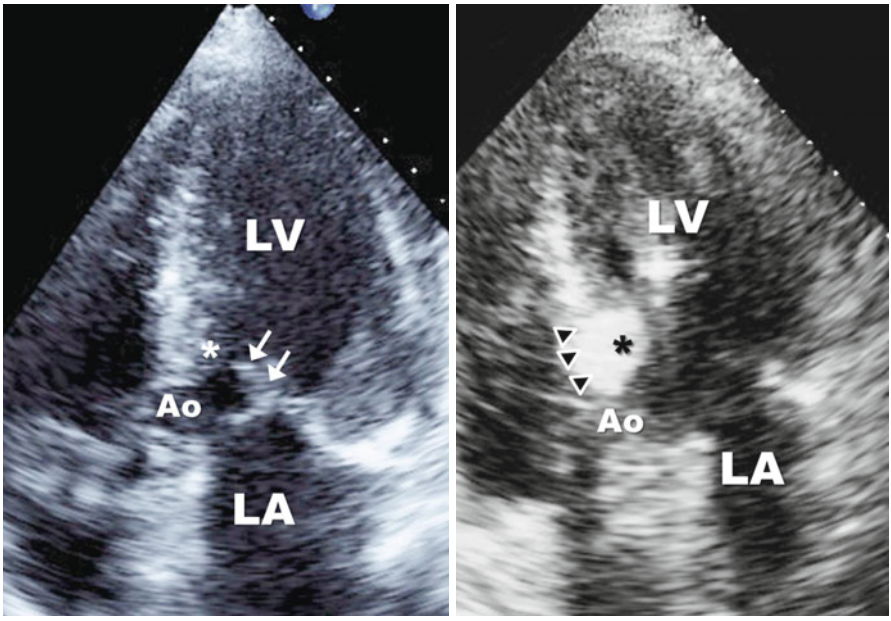

Fig. 31.3 Echocardiographic view during alcohol septal ablation. Panel A demonstrates the anterior leaflet of the mitral valve (*arrows*) making contact with the basal portion of the anterior interventricular septum (*) during systole. *Ao* aortic valve, *LV* left ventricle, *LA* left atrium. Panel B is alcohol (*arrowheads*) in basal anterior septum including the area where the anterior mitral leaflet makes contact (*)

block. The targeted myocardial region for ablation is that area of the basal septum where contact is made with the anterior leaflet of the mitral valve (Fig. 31.3) [2].

Once the target vessel or branch has been identified, angiographic contrast is injected through the coronary guide catheter and through the distal port of the inflated balloon catheter in the septal vessel. This is done to ensure that the inflated balloon completely occludes the septal vessel, so that upon injection, alcohol cannot leak back into the LAD, which is a potentially disastrous complication. Myocardial contrast echocardiography has taught us that contrary to what was originally thought, the entire septal branch need not be ablated in order to obtain a satisfactory hemodynamic result (Fig. 31.4).

Alcohol septal ablation is accomplished by injection of usually 1–2 mL of 96–98 % ethanol into the target septal branch. The alcohol is injected slowly, at a rate of approximately 1 mL/min. This is done to minimize complications, especially high-degree atrioventricular block. Immediately prior to alcohol injection, intravenous analgesia is administered in an effort to mitigate the pain associated with alcohol-mediated myocardial necrosis. During and immediately following alcohol infusion, the patient is scrupulously monitored looking for QRS widening, ST segment changes, the occurrence of complete heart block and for signs of hemodynamic deterioration.

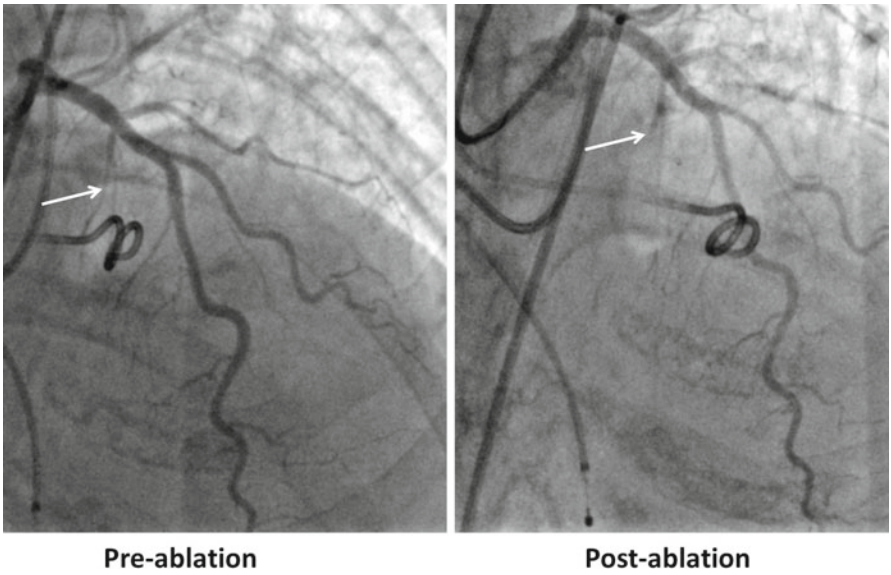

Fig. 31.4 Pre-ablation panel: Coronary angiogram showing the basal septal branch of the first septal perforator (*arrow*) which was documented by myocardial contrast echocardiography to be the target for alcohol ablation. Post-ablation panel: Ablated basal septal branch (*arrow*) following the slow injection of 1.25 cc of alcohol

Following alcohol septal ablation, patents remain in the coronary care unit for approximately 24 h, predominantly for monitoring, especially as relates to detecting ventricular arrhythmias and complete heart block. In general, if the patient has not required pacing, the temporary pacemaker is removed.

Data Interpretation

As a general rule, alcohol septal ablation is considered successful when an acute reduction in the resting or provoked left ventricular outflow gradient of greater than 50 % or to less than 20 mmHg has been achieved (Fig. 31.2). Comprehensive pressure sampling is usually performed given the dynamic nature of the left ventricular outflow gradient in HOCM. Frequently, the initial improvement in the outflow gradient appears to be lost on follow-up Doppler study the day following the procedure. The immediate gradient reduction is likely secondary to alcohol-induced septal necrosis and stunning, an effect which can be evanescent and is distinct from the permanent septal thinning and remodeling which is associated with progressive and long-lived gradient reduction seen on long-term follow-up.

To date, there have been no randomized studies comparing alcohol septal ablation to surgical myectomy in patients with medication-refractory HOCM. Meta-analyses of large observational series have suggested that septal ablation and

myectomy are comparable in terms of long-term survival and symptomatic relief with septal ablation leading to a higher rate of permanent pacemaker implantation [3–6]. There are suggestions that patients undergoing septal ablation have higher residual gradients as compared to patients treated surgically, however, the clinical significance of this finding is not clear.

Complications

The risk of procedural mortality following alcohol septal ablation is low. Recent series have reported in-hospital mortality of less than 1 % [3–6]. The reduction in procedural mortality over the years has paralleled the decline in the volume of alcohol used to accomplish gradient reduction. Approximately 75 % of the patients undergoing alcohol septal ablation will develop a right bundle branch block following the procedure which is in contrast to patients undergoing surgical myectomy who almost universally develop a left bundle branch block.

The most frequent complication of alcohol septal ablation is complete heart block. The decision to implant a permanent pacemaker in patients with heart block involves a clinical assessment of risk of recurrence and/or permanence of the heart block involving clinicians caring for the patient which usually involves electrophysiologic consultation. There is some variability in the threshold for pacemaker implantation, with a current frequency in the United States of approximately 10–15 % of ablation patients. There is a higher frequency of heart block and pacemaker implantation in the elderly given their higher frequency of intrinsic conduction system disease.

The most feared complication of septal ablation is the application of alcohol outside of the myocardial region targeted by myocardial contrast echocardiography. This can occur when alcohol leaks down the LAD through a nonocclusive balloon or when alcohol enters collateral channels (which may be below fluoroscopic imaging resolution) leading away from the targeted septal branch. The obvious result is infarction in an unintended myocardial region. The consequences depend on the involved area of myocardium and the volume of alcohol entering this region. Patients experiencing this complication may exhibit rapid clinical deterioration due to widespread acute myocardial infarction often with consequent pulmonary congestion. Mitral and tricuspid regurgitation as well as ventricular tachyarrhythmias are also possible in this subset of patients. Echocardiography, which is readily available during this procedure, is a key aid in confirming this diagnosis. Other rare coronary complications include coronary dissection, perforation, and thrombosis.

A potential longer-term complication of alcohol septal ablation is the facilitation of ventricular arrhythmias. Alcohol septal ablation does induce intramyocardial scar formation in a population of patients already prone to reentrant ventricular arrhythmias raising the possibility that the induced septal infarct could enhance the likelihood of sudden death in some patients. This concern has not, to date been realized as interrogation of defibrillators, implanted for primary prevention in HOCM patients undergoing septal ablation has not documented any signal for an increased

incidence of ventricular arrhythmias. Comparative analyses have similarly shown no increase in the incidence of sudden cardiac death in ablation patients when compared with similar populations undergoing surgical myectomy.

Clinical Vignette

A 67 year old, morbidly obese man with a history of prior coronary bypass surgery, COPD and obstructive sleep apnea presented with an 8 month history of progressive dyspnea on exertion, NYHA Class III in severity which severely limited his normal daily activities. Physical exam documented a bifid carotid pulse and a loud apical systolic murmur which increased by 1 grade following a Valsalva maneuver. Echocardiography revealed hyperdynamic left ventricular systolic function, basal septal hypertrophy with a thickness of 21 mm consistent with a diagnosis of hypertrophic cardiomyopathy. There were no noted abnormalities of the mitral valve or the subvalvular apparatus. Continuous wave Doppler study estimated an 80 mmHg subaortic gradient due to dynamic systolic anterior motion of the mitral valve with basal septal contact. Coronary artery angiography documented patent grafts to the distal LAD, right and left circumflex arteries. The LAD was occluded in its mid segment after the second diagonal branch.

Medical management with escalating doses of β-blocking agents and verapamil were ineffective in relieving the patient's symptoms. Due to prior coronary bypass surgery, medical comorbidities and patient preference ASA was recommended. The patient was referred to the cardiac catheterization laboratory where a 100 mmHg resting left ventricular outflow gradient was documented. Myocardial contrast echocardiography identified a basal branch of the first large septal perforating branch of the LAD as supplying the basal septum at the site of contact with the anterior leaflet of the mitral valve. Following the slow infusion of 1.25 mL of alcohol, the resting gradient was reduced to 20 mmHg. The patient required temporary pacing for 10 min following the injection of alcohol, but sinus rhythm returned shortly thereafter, albeit with the emergence of a right bundle branch block. Permanent pacemaker implantation was not required. On follow-up 3 months later, the patient reported marked clinical improvement with NYHA Class I symptoms. Echocardiography with Doppler study documented that the basal septum had remodeled to a maximal thickness of 17 mm with a resting outflow gradient of 20 mmHg.

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Chapter 32
Transcatheter Closure of Atrial Septal Defects and Patent Foramen Ovale

Francisco Garay, Qi-Ling Cao, and Ziyad M. Hijazi

Atrial Septal Defect

Secundum atrial septal defects (ASD) represent 6–10 % of all congenital cardiac anomalies and are twice as frequent in females than males. ASD leads to a left to right shunt which in turn produces right sided cardiac volume overload, increased pulmonary blood flow and eventually pulmonary arterial hypertension and pulmonary vascular disease. The closure of these defects can be achieved safely and efficiently by transcatheter methods [1, 2].

Indications

Closure of this defect is indicated in patients with evidence of a significant hemodynamic shunt which is usually documented by echocardiographically demonstrated right ventricular and atrial enlargement. Clinically, this is evident by the presence of a systolic ejection heart murmur with fixed splitting of S2. Patients may or may not have overt symptoms, including shortness of breath, fatigue and palpitations.

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Contraindications

- The development of non-reactive pulmonary vascular disease. This is rare (about 5 % of patients) and usually occurs in adults older than 40 years of age. A pulmonary vascular resistance indexed higher than 7 Wood units after a trial of vasodilators, such as inhaled nitric oxide is a contraindication for closure.
- Systemic or local infection within 1 month of the procedure.
- Bleeding disorders or other contraindications to aspirin therapy, unless other antiplatelet agents such as clopidogrel can be used for 6 months.
- Presence of intracardiac thrombus.
- Nickel allergy is a relative contraindication. This issue has not been a clinically important one even in patients with documented nickel allergy.
- Patients with primum or sinus venosus types of atrial defects are in general, not candidates for non-surgical closure.

Equipment

The *Amplatzer® Septal Occluder* (ASO) consists of 2 nitinol wire mesh discs connected by a 3–4 mm waist (Fig. 32.1). The device size is determined by the diameter of its connecting waist with available sizes ranging from 4 to 40 mm. The two flat discs extend radially beyond the connecting waist to secure anchorage. The left atrial disc is larger than the right atrial disc. Dacron polyester patches are sewn into each disc and the connecting waist to increase thrombogenicity of the device. The ASO is delivered through a sheath ranging from 6 to 12 F diameter and lengths of 60–80 cm which is advanced from the right femoral vein, through the right atrium across the interatrial septum into the left upper pulmonary vein. The ASO is pushed through the sheath by a delivery cable which is unscrewed when proper location and deployment are documented.

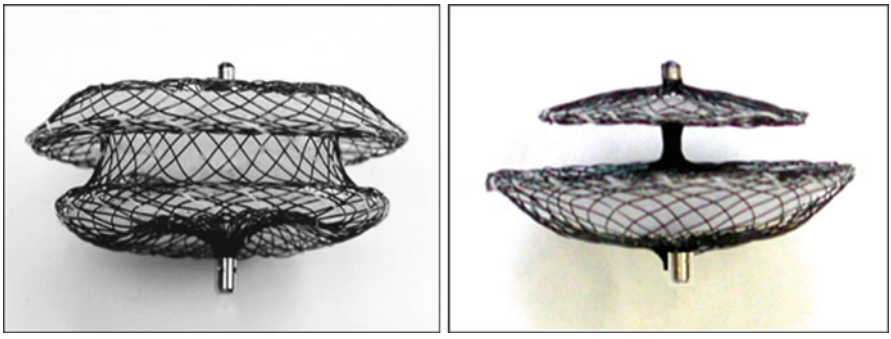


Fig. 32.1 The Amplatzer Septal Occluder (*right*) and the Amplatzer PFO Occluder (*left*). Both devices are made of Nitinol wire mesh

The *Amplatzer® Sizing balloon* is optional but recommended to facilitate correct device sizing.

The *Gore Helex Septal Occluder®* is a low-profile device constructed from a single nitinol wire with ePTFE bonded to the nitinol frame. The device is available in 5 sizes, ranging in diameters of 15–35 mm. As recommendations for the use of this device advise a ≥2:1occluder to defect diameter ratio, the *Gore Helex* is most usually applied to pediatric patients.

Technique

One should review all previous data related to the patient and the defect to be closed and ensure that appropriate devices and delivery systems are available. Aspirin 81–325 mg should be started 48 h prior to the procedure. Alternatively, clopidogrel 75 mg could be used.

The procedure is performed under either transesophageal echocardiography (TEE) or intracardiac echocardiography (ICE) guidance. If TEE is used, due to the length of the procedure and for patient's comfort, the procedure should be done under general endotracheal anesthesia. If the procedure is performed under ICE guidance, mild sedation is given. The procedure is most often performed via femoral venous access. Heparin is administered to maintain an activated clotting time (ACT) above 200 s at the time of device deployment. Broad spectrum antibiotic administration is recommended for the procedure (eg. cefazolin 1 g iv), the first dose at the time of the procedure and two additional doses 6–8 h apart. Right heart catheterization is performed to measure pulmonary artery pressure, calculate pulmonary vascular resistance and shunt (Qp:Qs) ratio. The pulmonary vascular reactivity can be evaluated if necessary. TEE or ICE (Figs. 32.2 and 32.3) images are obtained to assess the ASD anatomy (location, size, additional defects and rims) [3]. It is important to fully evaluate the atrial septal anatomy as well as that of adjacent structures to ensure that the device will be properly seated following deployment.

The angiographic catheter is advanced into the left atrium from the inferior vena cava into the right upper pulmonary vein. An angiogram is then performed (Fig. 32.4a) to evaluate the atrial septal length and shape. A stiff guide wire is advanced just distal to the catheter tip (Fig. 32.4b). The angiographic catheter is exchanged for a sizing balloon (Fig. 32.4c). The balloon is placed across the defect under fluoroscopic and echocardiographic guidance and then inflated with diluted contrast until the left-to-right shunt ceases as observed by color flow Doppler on TEE or ICE. The indentations in the balloon made by the margins of the ASD are measured on echocardiographic or fluoroscopic images (Fig. 32.4c). Usually the echo measurements are more reliable than the fluoroscopic measurements. A device approximately 1–2 mm larger than the measured sizing balloon diameter is selected. The sizing balloon is removed and a delivery sheath is advanced over the super stiff guide wire to the left upper pulmonary vein (Figs. 32.4d and 32.5b). Extreme care must be exercised to not allow passage of air inside the delivery sheath.

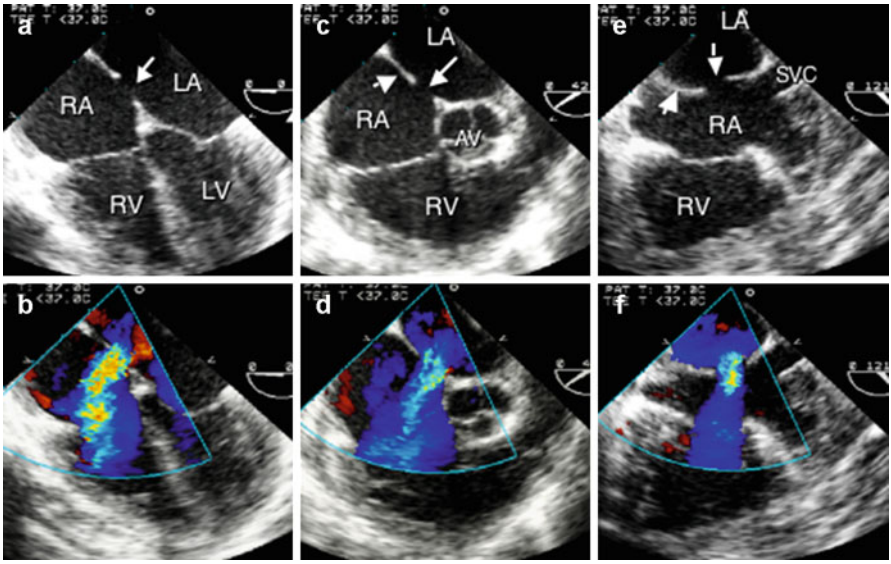
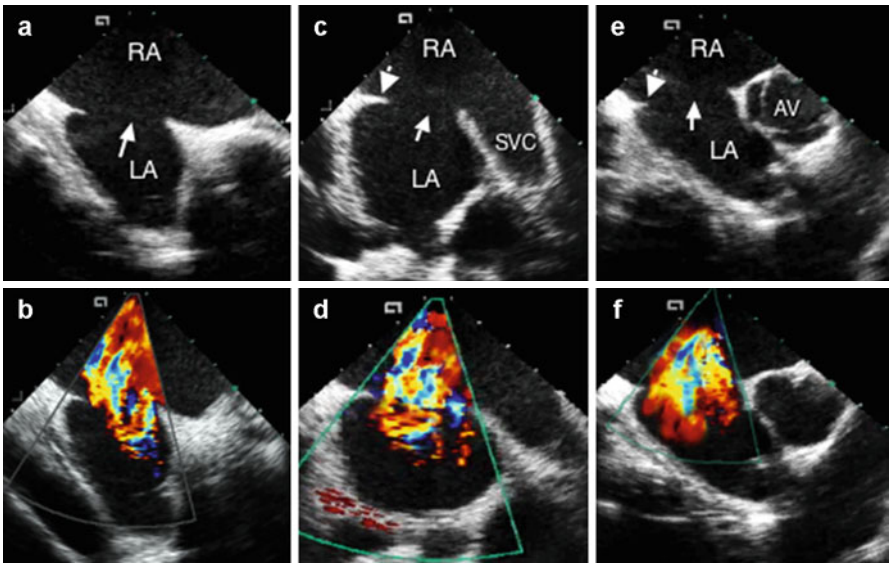


Fig. 32.2 Transesophageal echocardiographic images obtained to assess the ASD anatomy. (**a**, **b**) four chamber view without and with color Doppler demonstrating the ASD (*arrow*) and left-to-right shunt. (**c**, **d**) short axis view without and with color Doppler demonstrating the ASD (*arrow*), the anterior rim near the aortic valve and posterior rim (*arrowhead*). (**e**, **f**) bi caval long axis view without and with color Doppler demonstrating the ASD (*arrow*), the superior rim near the superior vena cava and inferior rim near the inferior vena cava (*arrowhead*). *RA* right atrium, *LA* left atrium, *RV* right ventricle, *LV* left ventricle, *SVC* superior vena cava



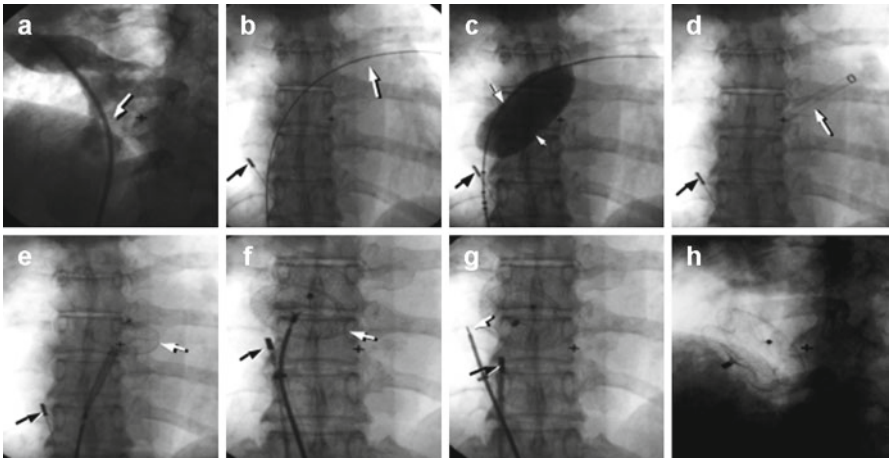


Fig. 32.4 Cine fluoroscopic images in a patient with a large secundum ASD during closure with the Amplatzer device under intracardiac echocardiographic guidance. Black arrow is the AcuNav catheter for intracardiac echocardiographic images. (**a**–**h**) were obtained in the hepatoclavicular projection and the remaining images in straight frontal projection. (**a**) angiogram in the right upper pulmonary vein demonstrating the left-to-right shunt through the ASD (*arrow*). (**b**) cine image during passage of the guide wire (*white arrow*) through the ASD to the left upper pulmonary vein. (**c**) cine image during balloon sizing demonstrating the "stop-flow" diameter of the defect (*white arrows*). (**d**) cine image during passage of the delivery sheath (*white arrow*) to the left upper pulmonary vein. (**e**) cine image during deployment of the left atrial disk (*white arrow*) in the left atrium. (**f**) cine image during deployment of the right atrial disk (*white arrow*) in the right atrium. (**g**) cine image immediately after the cable (*white arrow*) was released from the device. (**h**) final angiogram in the right atrium in the showing good device position

Fig. 32.3 Intracardiac echocardiographic images obtained to assess the ASD anatomy. (**a**, **b**) Septal view without and with color Doppler demonstrating the ASD (*arrow*) and left-to-right shunt. (**c**, **d**) bi caval long axis view without and with color Doppler demonstrating the ASD (*arrow*), the superior rim near the superior vena cava and inferior rim near the inferior vena cava (*arrowhead*). (**e**, **f**) short axis view without and with color Doppler demonstrating the ASD (*arrow*), the anterior rim near the aortic valve and posterior rim (*arrowhead*). Note, with ICE, the left atrium is in the bottom of image and right atrium in toip which is in contrast with TEE images. *RA* right atrium, *LA* left atrium, *SVC* superior vena cava

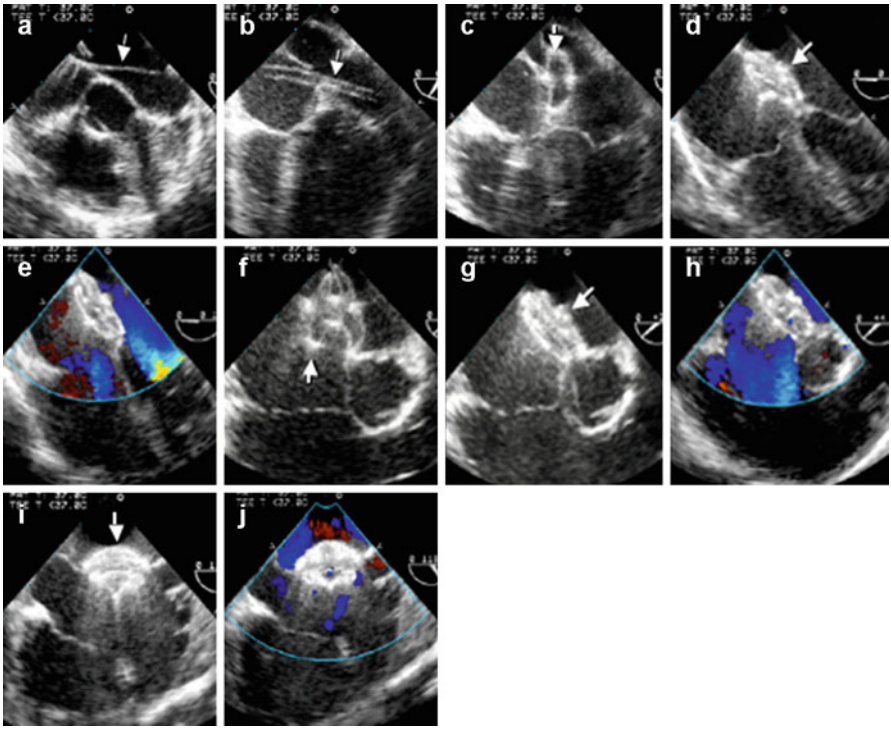


Fig. 32.5 Transesophageal echocardiographic images in the same patient as Fig. 32.2 demonstrating the steps of closure. (**a**) passage of guide wire (*arrow*) in 4-chamber view to the left atrium. (**b**) passage of the delivery sheath (*arrow*) in 4-chamber view to the left atrium. (**c**) deployment of the left atrial disk (*arrow*) in 4-chamber view in the left atrium. (**d**, **e**) device release (*arrow*) in 4-chamber view without and with color Doppler demonstrating good device position. (**f–h**) deployment of the right disk (*arrow*), device and assessment of position in short axis view without and with color Doppler. Device looks good and no residual shunt. (**i**, **j**) bi caval view without and with color Doppler demonstrating good device position

The device, attached to a delivery cable is advanced to the tip of the sheath. Then the cable and delivery sheath are pulled back as one unit to the middle of the left atrium. This position and the next steps are verified under fluoroscopy or TEE/ICE (Figs. 32.4, 32.5 and 32.6). The left atrial disc is deployed by pulling back the sheath maintaining the cable position and taking care of not to interfere with the atrial appendage. Finally withdrawing the delivery shearth over the cable, the connecting waist and the right atrial disc are deployed in the ASD itself and in the right atrium respectively.

Proper device position can be assessed by fluoroscopy where both discs are seen parallel to each other and separated from each other by the atrial septum (Fig. 32.4h). The echocardiogram (TEE/ICE) must demonstrate the presence of one disc in each atrial chamber. If the position is uncertain or questionable, after all these maneuvers, the device can be recaptured and repositioned. After the position of the device has been verified, the device is released from its delivery cable. Assessment of the final result of the closure procedure is performed immediately with TEE or ICE, and 24 h later with transthoracic echocardiography.

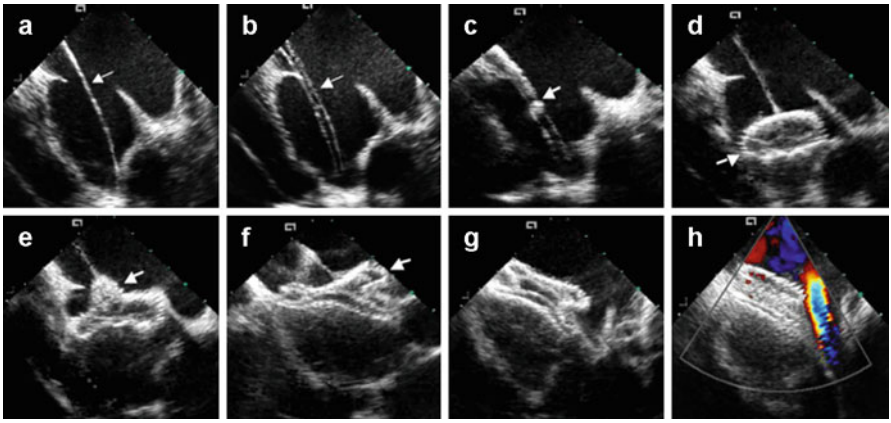


Fig. 32.6 Intracardiac echocardiographic images (ICE) during various stages of device deployment in the same patient as Fig. 32.3. (**a**–**c**) views between septal and bicaval views demonstrating passage of guide wire (*arrow*) (**a**) delivery sheath (*arrow*) (**b**) and the 32 mm device inside the sheath (*arrow*) (**c**). (**d**) deployment of the left disk (*arrow*) in the left atrium. (**e**) deployment of the connecting waist (*arrow*) in the defect itself. (**f**) deployment of the right disk (*arrow*) in the right atrium. (**g**) device release demonstrating good device position. (**h**) bicaval view showing good flow in the superior vena cava and good device position

Patients are treated with daily aspirin for 6 months and endocarditis prophylaxis when necessary for 6 months after the procedure. Full activity including competitive and contact sports are allowed after 4 weeks of implantation.

Data Interpretation

Measurement of Qp:Qs ratio in the catheter laboratory is prone to errors, therefore, evidence of the right-sided volume overload relies mainly on echocardiographic findings. In adults older than 65 years and with large defects, it is prudent to measure the LA pressure during balloon occlusion of the defect to evaluate the LV compliance. If an increase to > 18 mm of Hg in the LA pressure is observed, then a LV conditioning treatment is started with anticongestive and afterload therapy for 48-72 hours prior to attempting the closure procedure [4].

Complications

Air embolism meticulous technique should be used to prevent air entry into the left sided cardiac chambers which may result in coronary ischemia and stroke. Free flow of blood from the sheath must be allowed, avoiding forceful negative pressure aspiration.

Device embolization if this occurs the device has to be removed either surgically or by transcatheter snare techniques. One should avoid pulling the device across valves.

Prolapse of the left disc across the defect during deployment: especially in patients with large defects and deficient antero/superior rims, resulting in left atrial disc prolapse through the anterior/superior part of the ASD. Several technical maneuvers can correct such malpositioning [5, 6]

Arrhythmias an increase in atrial arrhythmias occurs following the procedure, but this is a transient phenomenon that usually resolves within 6 months. Heart block has been rarely reported [7].

Right atrial and aortic root perforation Extremely infrequent (0.1 %). To minimize this risk, device oversizing should be avoided [8].

Patent Foramen Ovale (PFO)

The foramen ovale is created by the overlap of septum primum and septum secundum. Anatomic variants exist (flap type, tunnel type and PFO with aneurysmal septum primum). It has been described to remain probe-patent in 25 % of the population, being a potential source of paradoxical emboli when a right-to-left shunting is present. PFO has been demonstrated with a higher than normal prevalence in cryptogenic stroke patients less than 55 years old and an association has been suggested with an aneurysmal septum primum increasing this risk. Additionally, conditions associated with elevated RA pressure (chronic pulmonary disease, recurrent pulmonary embolus) and hypercoagulable states increase the potential for right-to-left shunt and paradoxical emboli. In spite of medical management the risk of stroke recurrence remains significant.

Several devices have been designed to specifically close PFO's, however ASD closure devices have also been used for PFO closure. The Amplatzer® PFO Occluder is a self-expandable, double-disc device made from a Nitinol wire mesh 0.005–0.006 in. in diameter (Fig. 32.1). The two discs are linked together by a connecting waist 2 mm in diameter and 4 m in length. The discs are filled with polyester fabric sewn securely to each disc by a polyester thread, that increases the device closing ability. The device is similar in design to the ASD occluder, differing in that the right atrial disc is larger than the left one.

Indications Patients with recurrent cryptogenic stroke due to presumed paradoxical embolus through a PFO and who have failed conventional medical therapy [9]. This procedure is usually performed off-label with an ASD device in the United States as PFO closure has not yet been approved by the FDA. Randomized trials have been negative in terms of the composite endpoint, but have suggested prevention of recurrent paradoxical embolism-induced stroke in patients randomized to device closure.

Contraindications The same as for secundum ASD closure.

Equipment The delivery system is similar to the ASD delivery system.

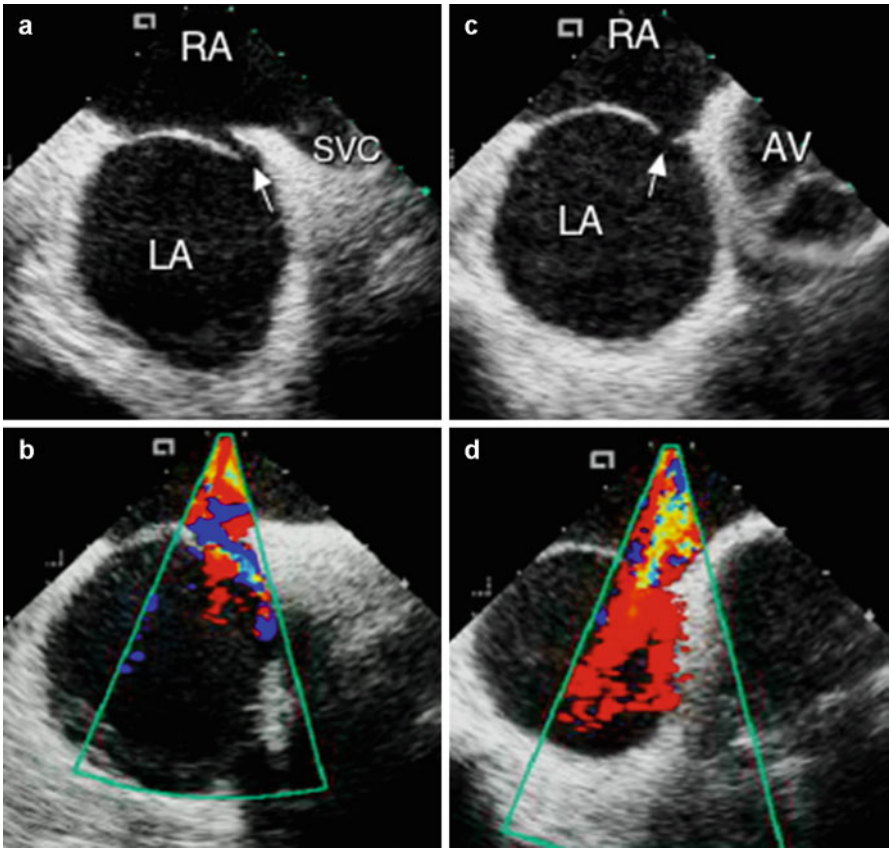


Fig. 32.7 Intracardiac echocardiographic images to assess anatomy of the PFO in a patient who sustained a stroke. (**a**, **b**) septal view without and with color Doppler demonstrating presence of a PFO (*arrow*) with left-to-right shunt. (**c**, **d**) short axis view demonstrating the PFO (*arrow*) and left-to-right shunt

Technique Similar to the ASD procedure [10]. A sheath is inserted into the femoral vein. Heparin and antibiotics are administered. The procedure is performed under general anesthesia or conscious sedation depending on the imaging modality used to guide deployment (TEE or ICE). Assessment of PFO anatomy and rims (Fig. 32.7) should be performed (a minimal distance of 9 mm to the SVC and to the aortic root is required to implant the device). In cases with an aneurysmal septum a larger device is preferred. Unlike the ASD closure procedure, balloon sizing is not performed. The device deployment is identical to ASD closure (Fig. 32.8).

Data interpretation A contrast bubble study with and without Valsalva maneuver under echocardiography or transcranial Doppler (TCD) is necessary to demonstrate right-to-left interatrial shunting and is repeated at the end of the procedure to

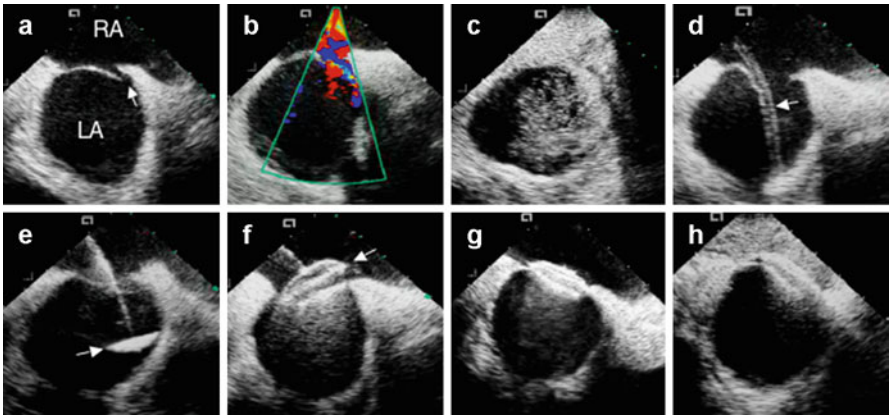


Fig. 32.8 Intracardiac echocardiographic images in same patient as Fig. 32.7 during various stages of device closure. (**a**, **b**) septal view without and with color Doppler demonstrating the PFO (*arrow*). (**c**) contrast bubble study at rest showing passages of bubbles from right atrium to left atrium. (**d**) passage of the delivery sheath (*arrow*) to the left atrium. (**e**) deployment of the left disk of a 25 mm Amplatzer PFO device into the left atrium. (**f**) deployment of the right disk (*arrow*) in the right atrium. (**g**) device has been released showing good position. (**h**) repeat contrast bubble study showing negative result at end of Valsalva maneuver

document successful closure. Closure rates using the Amplatzer PFO device have been over 95 % [10].

Complications

Right atrial and aortic root perforation Extremely infrequent. It has motivated the company to introduce the septal measurements, emphasizing the distance of the free right atrial wall from the defect and device.

Entrapment of prominent Eustachian Valve on the delivery cable it causes no problem with the deployment, however to avoid the avulsion of the Eustachian Valve, it is suggested to advance the delivery sheath to the hub of the right disc prior to releasing the cable from the device.

Clinical Vignettes

Case 1 (ASD Closure)

An asymptomatic 28year old female patient was diagnosed to have a secundum type ASD. On a routine scheduled physical examination she was noted to have a widely split S2 and a grade 2 systolic ejection murmur heard best at the left upper sternal

border. The lungs were clear to auscultation. TEE revealed a large secundum ASD measuring 26 mm with left-to-right shunting and evidence of right ventricle volume overload. Cardiac catheterization performed under conscious sedation and ICE guidance showed a significant left-to-right shunt with calculated Qp:Qs ratio of 4.1:1, the mean pulmonary artery pressure was 18 mm of Hg and PVR was 1.3 Wood units. ICE revealed a large ASD measuring 26 mm in diameter with left-to-right shunt and a deficient anterior rim (Figs. 32.3 and 32.6).

A 32 mm Amplatzer septal occluder device was chosen and a 11 Fr Hausdorf long sheath was used to deliver the device. ICE revealed complete closure. The patient was discharged 24 h later with TTE showing proper device position and no residual shunt.

Case 2 (PFO Closure)

A 42-year old female patient chronically treated with aspirin, presented reporting the sudden onset of right-sided weakness and dysarthria while driving her car. On examination, she was noted to be aphasic with a facial droop and right upper and lower extremity hemiplegia. She was treated with heparin and aspirin with clinical resolution of most symptoms overnight. One day later, an MRI of the brain revealed an infarct in the distribution of the left middle cerebral artery with evidence for a prior, clinically unrecognized event in the right parietal cortex.. Work-up was remarkable solely for a PFO with right-to-left shunting and an atrial septal aneurysm.

She was referred for device closure for recurrent stroke in the setting of antiplatelet therapy. The procedure was done under ICE guidance (Fig. 32.7) and a 25 mm Amplatzer PFO device was successfully implanted (Fig. 32.8). Her ICE and TCD were negative for residual shunt after the closure.

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Chapter 33
Balloon Valvuloplasty

Ted Feldman

Balloon valvuloplasty is used to treat stenotic lesions of the pulmonic, aortic, and mitral valves. The patient populations appropriate for this procedure are highly different for each of the three valve types. The major contraindication to balloon valvuloplasty in any of these valve positions is severe valvular regurgitation.

Aortic Valvuloplasty

Indications

Balloon aortic valvuloplasty (BAV) is first choice therapy for aortic stenosis in children and young adults, age 21 years or less. In older adult patients, it is infrequently a first choice therapy because restenosis occurs in most patients between 6 months and 2 years after the therapy is initially applied. It is indicated as a bridge to surgery in hemodynamically unstable high-risk patients prior to aortic valve replacement, for palliation in patients with serious comorbid conditions, and prior to noncardiac surgery in some patients. The most common use of BAV in current practice is as a bribge to TAVR for patients with debilitating symptoms or refractory heart failure. It is also increasingly used for patients who are not candidates for either aortic valve replacement surgery or TAVR, as a palliative treatment for temporary relief of symptoms. It is not used as an alternative to aortic valve replacement. Patients are selected on the basis of symptoms of angina, dyspnea or syncope in association with echocardiographic evidence for aortic stenosis, usually with an aortic valve area <0.8 cm^2, although patients with valve area 0.8–0.9 cm^2 are occasionally treated.

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Contraindications

The major contraindications to BAV are the patient who is a candidate for aortic valve replacement, and then among patients in whom BAV is desired, inability to accomplish retrograde catheterization or contraindications to transseptal catheterization are strong relative contraindications.

Equipment

10–14F sheaths for arterial or venous approaches
0.032″ & 0.035″ extra-stiff 260–300 cm length guidewires
Transseptal sheath & needle for antegrade BAV
Temporary pacemaker
PA catheter (Swan-Ganz)
percutaneous suture closure devices
18–24 mm balloon catheters with 120 cm shaft for retrograde BAV
26 mm Inoue balloon catheter for antegrade BAV

Techniques

The techniques for performing aortic valvuloplasty include the conventional retrograde approach (Fig. 33.1) and the less frequently utilized antegrade transseptal approach [1]. Retrograde valvuloplasty requires a 10–12 French arterial sheath. After placement of a large sheath, the valve is crossed retrograde, and a balloon catheter ranging from 18 up to 24 mm diameter is passed retrograde across the valve and inflated to relieve the stenosis. The balloon size is usually estimated from the annulus diameter on transthoracic echo or the short axis of the annulus diameter on TEE. Rapid right ventricular pacing is used as a method to diminish balloon "watermelon seeding" during balloon inflations. Without this adjunct, ventricular systole, especially in patients with preserved left ventricular systolic function, ejects the balloon during attempts to inflate it in the stenotic aortic valve. Burst pacing at between 140 and 200 beats per minute effectively reduces cardiac output sufficiently to allow the balloon to be positioned stably for inflations. Shorter balloons can thus be used, which diminishes the time of the inflation-deflation cycle. Temporary pacing is also needed if there is underlying bundle branch block.

The use of suture preclosure has diminished the challenges in managing the large arterial puncture [2]. Using a single 10 French Perclose device or one or two 6

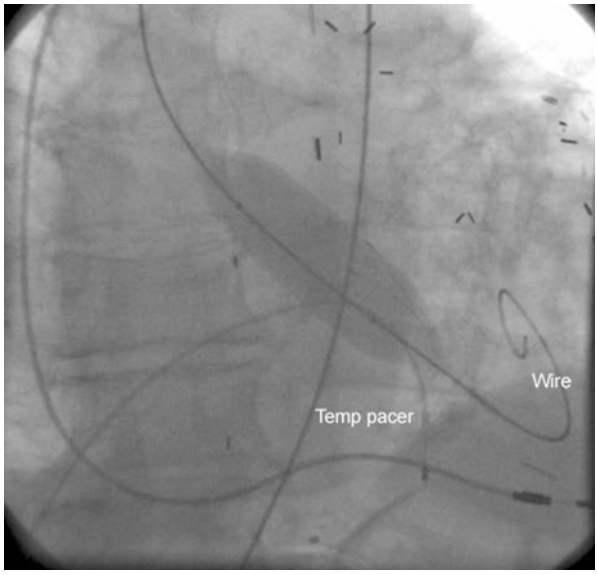

Fig. 33.1 Retrograde BAV. A curved giudewire is placed across the aortic valve into the left ventricular (LV) apex from the retrograde femoral arterial approach. A temporary pacemaker is used to pace the LV at 160–200 bpm while the balloon is inflated

French Proglide devices, immediate hemostasis can be obtained in the vast majority of patients, without any need to reverse the heparin anticoagulation.

Antegrade BAV have been described. A 14 French sheath can be placed in the right femoral vein to allow transseptal access and antegrade passage of a wire loop through the circulation, followed by balloon placement. Venous preclosure may be used as well, which similarly simplifies the management of the large venous puncture. Antegrade valvuloplasty may be performed with a conventional balloon or with an Inoue balloon. The valve areas achieved with the Inoue device are significantly greater than with a conventional balloon. The antegrade approach is more complex technically, but has the advantages of eliminating the need for a large arterial puncture, allowing more stable positioning of the balloon in the valve, and facilitating the delivery of larger balloon into the valve orifice. Since the routine use of rapid pacing the antegrade approach is rarely used.

Data Interpretation

Interpretation of hemodynamic data during the procedure is based on measurement of transvalve pressure gradient and cardiac output with calculation of valve areas (Fig. 33.2) [3]. Most patients have an initial aortic valve area between 0.4 and 0.8 cm^2. Typical post-procedure results involve increases in valve area up to 0.9–1.2 cm^2. One standard definition of procedure success is a 50 % increase in valve area or a 50 % decrease in mean transvalvular pressure gradient.

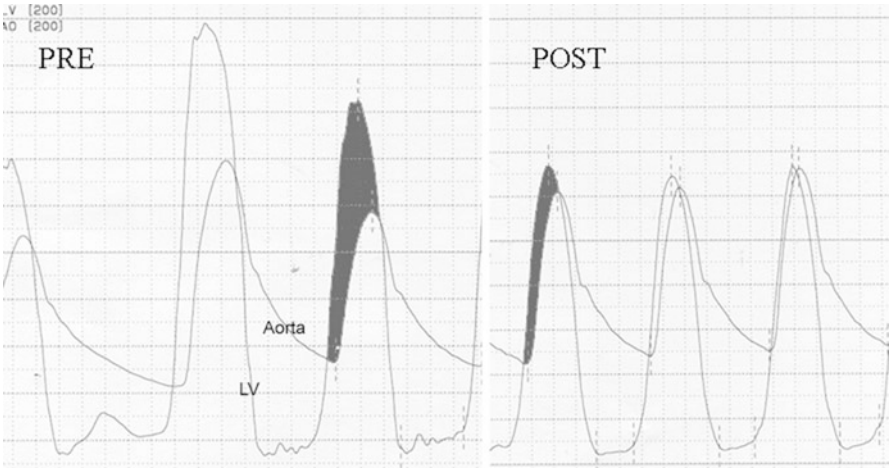

Fig. 33.2 Transaortic valve pressure gradient before and after BAV. The left panel shows a mean gradient of 45 mmHg (*shaded area*), representing the difference between the left ventricular and aortic pressures. The valve area was 0.6 cm^2. After BAV the mean gradient has decreased to 12 mmHg, and the valve area has increased to 1.3 cm^2. *Aorta* aortic pressure, *LV* left ventricular pressure

Complications

Major complications of the procedure are vascular access complications, damage to the aortic valve, or cardiac perforation. Large vascular sheaths are used for either venous or arterial access. Bleeding complications can be common and transfusion is needed in 25 % of patients when manual compression is used for arterial hemostasis. Bleeding complications are minimized by the use of suture closure techniques following the procedure. Some patients have dramatic hypotension and left ventricular failure immediately following balloon inflations, which in some cases leads to fatality on the catheterization laboratory table. Permanent pacemakers for heart block are required in 1 % or 2 % of patients, especially if underlying bundle-branch block is present to begin with. Hospital mortality is 5–8 % in this elderly, highly sick patient population when BAV is done as primary therapy, and probably less when BAV is done as a bridge to TAVR [4].

Clinical Vignette

An 84 year old man presents with CHF and is found to have aortic stenosis with a Doppler estimated aortic valve area of 0.6 cm^2. The transvalve mean and peak gradients are 54 and 76 mmHg, and left ventricular function is moderately depressed with ejection fraction 40 %. He has a history of CABG at age 70 and then again at age 78

years. The ECG shows atrial fibrillation with a rate of 85 bpm. Angiography shows a patent LIMA to LAD, patent native RCA, and occluded native and graft circumflex supply. In addition he has chronic kidney disease and recently diagnosed lung cancer.

His STS risk score is 16% and due his untreated cancer and frailty he is felt not to be a candidate for TAVR. Thus, balloon valvuloplasty is an attractive palliative therapy. BAV was performed using the antegrade approach. Right femoral venous 6F access was obtained, and a 6F Closer S device was used to place a suture. Baseline right heart pressures were measured. A 14F sheath was placed. After transseptal puncture, baseline transaortic gradient was assessed & valve area calculated. A balloon flotation was passed from LA to LV, and then antegrade across the aortic valve into the descending aorta. A guidewire was passed through the balloon catheter and snared in the descending aorta. The transseptal catheter was exchanged for a Inoue 26 mm balloon. This was passed over the wire to the aortic valve and inflated once to accomplish valve dilatation. Final transaortic valve pressure gradients were measured and valve area calculated. The 14F venous sheath was removed with pre-placed suture closure. He was discharged from the hospital the next morning.

Pulmonic Valvuloplasty

Indications

Balloon valvuloplasty (PBV) is the treatment of choice for patients with pulmonic stenosis. It is indicated for patients with pulmonic stenosis and symptoms of exertional dyspnea, angina, syncope, or presyncope. Asymptomatic patients with normal cardiac output and peak gradient greater than 50 mm should be treated as well. Treatment is controversial in patients who are asymptomatic with normal cardiac output and peak gradient between 30 and 50 mmHg. Asymptomatic patients with gradients less than 30 mmHg should not be treated with balloon valvuloplasty. The treatment is highly durable with clinical improvement in symptomatic relief in the vast majority of patients lasting for decades [5–6].

Contraindications

The major contraindication is more than moderate pulmonic insufficiency.

Equipment

12–14 F sheaths for femoral venous access
Dual lumen catheter
0.035″ & 0.038″ extrastiff 260–300 cm length guidewires

percutaneous suture closure devices
22 & 24 mm balloon catheters with 120 cm shaft
26–30 mm Inoue balloon catheters

Technique

The procedure is performed via femoral venous access [7]. A guidewire is passed across the stenotic pulmonic valve, and transvalve pressure gradient measured with a dual lumen catheter. A balloon catheter is passed across the valve. It is important to measure the valve annulus diameter using echocardiography prior to the procedure so balloon sizing can be appropriate. A single large balloon is adequate in the majority of patients. A balloon to annular diameter ratio of 1.2 is ideal. Occasional patients require double balloon technique to achieve an adequate result. The Inoue balloon may be used and is available in diameters up to 30 mm, which will be suitable for the majority of patients.

Data Interpretation

Transvalvular pressure measurement is used before and during the pressure to assess the degree of stenosis. Gradient >50 mmHg at rest is typical. Valve areas are not routinely reported for this procedure, but are useful to follow and should be measured in adult patients. After valvuloplasty the PA pressure changes little. Diminished RV pressure is mostly responsible for the decreases in gradient.

Complications

The major complications include vascular access bleeding, which is not ordinarily problematic because the access is venous. Pulmonic insufficiency may result and is usually tolerated acutely [8].

Clinical Vignette

A 43 year old man presents with fatigue. After a heart mumur is noted he is found to have congenital pulmoinc stenosis on echo. The mean gradient is estimated to be 80 mmHg and there is no pulmonic regurgitation. There is RV hypertrophy without chamber enlargement. The pulmonic annulus diameter measured 23 mm.

Right femoral 14 access was obtained. Arterial pressure was monitored by cuff. Pressures were measured, and after the transpulmonic gradient was confirmed, a 28 mm Inoue balloon was passed into the valve and inflated twice. The balloon was removed and a double lumen catheter passed back across the valve. Repeat pressure measurement showed a decrease in transpulmonic gradient to 35 mmHg. The single right femoral venous sheath was removed with manual compression. After 6 h of bed rest the patient was ambulated and then discharged.

Mitral Valvuloplasty

Indications

Balloon mitral valvuloplasty is also referred to as balloon mitral valvotomy (BMV), or percutaneous transvenous mitral commissurotomy (PTMC). BMV is indicated for symptomatic patients with mitral valve area 1.5 cm^2 or less and favorable valve morphology [9]. The most important contraindication is left atrial thrombus seen on transesophageal echo, which is necessary for screening all patients, in the absence of moderate to severe mitral regurgitation. Favorable leaflet morphology is related to the pliability of the leaflets, symmetry of commissural fusion, and the degree of leaflet calcification and subvalvular deformity. Asymptomatic patients with valve area less then 1.5 cm^2 and pulmonary artery systolic pressure greater than 50 mm at rest or 60 mm with exercise, may be treated as well. Severely symptomatic patients with highly calcified valves who are high risk for mitral valve replacement can be treated as well. Treatment for asymptomatic patients with new atrial fibrillation is controversial. Patients with mild mitral stenosis should not be treated with balloon valvotomy.

Contraindications

The most important contraindication for BMV is left atrial thrombus, which may be seen in as many as 20 % of patients screened for the procedure, even among those taking coumadin anticoagulation therapy. The addition of more intense anticoagulant therapy will result in resolution of the thrombus in most patients within 6 t o 12 weeks, allowing performance of the procedure at a later time.

Technique

Numerous techniques exist, among them the double balloon technique, Inoue balloon technique, metal commissurotome, and retrograde transarterial technique [10]. Dilatation is usually performed via an antegrade approach using transseptal puncture. The most commonly used device for catheter mitral valvotomy worldwide is the Inoue balloon catheter. This is a novel single balloon that inflates in three stages

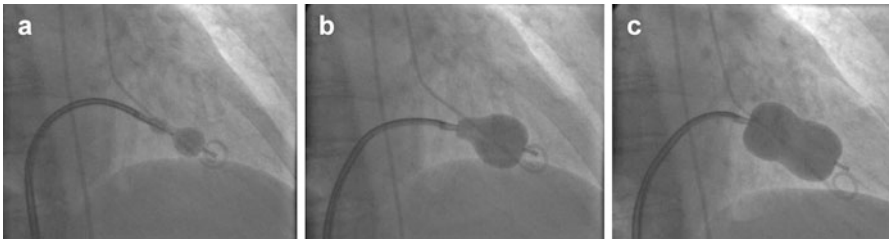

Fig. 33.3 Sequence of balloon inflation for Inoue technique BMV. (**a**) Partially inflated Inoue balloon, across the mitral valve, in the left ventricle. (**b**) the balloon is pulled back to engage the mitral leaflets and (**c**) fully inflated to split the valve commissures

(Fig. 33.3). After the balloon is passed into the left atrium, the front portion is inflated in the manner a pulmonary artery catheter is inflated, and then the balloon is maneuvered across the mitral valve. This is accomplished with the aid of a steering stylette with a preformed anterior curve. The balloon is pulled back until it engages the stenotic mitral orifice. As the balloon is inflated, the middle section opens, applying pressure to the commissures. The balloon may be inflated with increasing volumes of contrast with resultant increases in diameter. After each balloon inflation the pressure gradient can be measured and mitral regurgitation assessed either by echocardiographic visualization or by repeat ventriculography. Successive inflations at larger balloon diameters is then performed until either a minimum gradient is achieved or mitral regurgitation begins to increase. This is called the step-wise method for commissurotomy.

The procedure may also be accomplished using conventional balloons. Typically two balloons of 15–20 mm diameter are used together. Two wires must be passed through the transseptal puncture to accomplish this. The wires are looped in the ventricular apex and sometimes passed into the aorta to provide stability for advancing the balloons into the mitral orifice. The balloon catheters for this approach are longer than the Inoue balloon and either the balloon catheter tips or the guide wire may cause ventricular apical perforation. It is also possible to pass balloons retrograde from the aorta through the left ventricle and across the initial valve. This approach avoids transseptal puncture, but requires large bilateral femoral sheaths.

The metal commissurotome is a mechanical metal dilator placed on a catheter shaft. This can be passed into the mitral valve and opened to split the commissures. The major advantage of this device is that it is a reusable instrument and is especially attractive in parts of the world where catheter reuse is the rule rather than the exception. A disadvantage is the large French size and rigidity of the metal working end of this device. It can be difficult to position in the mitral valve, and cardiac perforation is a risk. This device is not available in the United States.

Equipment

14F sheath for R femoral venous access
Transseptal sheath & needle

PA catheter (Swan-Ganz)
percutaneous suture closure devices
26, 28 and 30 mm Inoue balloon catheters

Data Interpretation

Screening transthoracic echo is the first critical step in patient evaluation. The valve leaflets and subvalvular apparatus must be examined for patient selection for the procedure. An echocardiographic scoring system assigning 4 points to each of these categories (maximum score 16) has been devised as a rough guide to patient selection. Patients with low score (6–9) have the best long-term results. Patients with higher scores may be treated, recognizing that results will be less durable. Poor candidates for surgery may be treated even with severe valve deformity (echo score 10–16) as a palliative procedure. During the procedure results are assessed by hemodynamic measurement of the transvalvular pressure gradient (Fig. 33.4). The mean gradient typically decreases from 12–14 to 4–6 mmHg. Results are also assessed by echo measurement of the mitral valve area. Both left ventriculography in the cath lab and Doppler echo are used to assess mitral regurgitation before and after BMV.

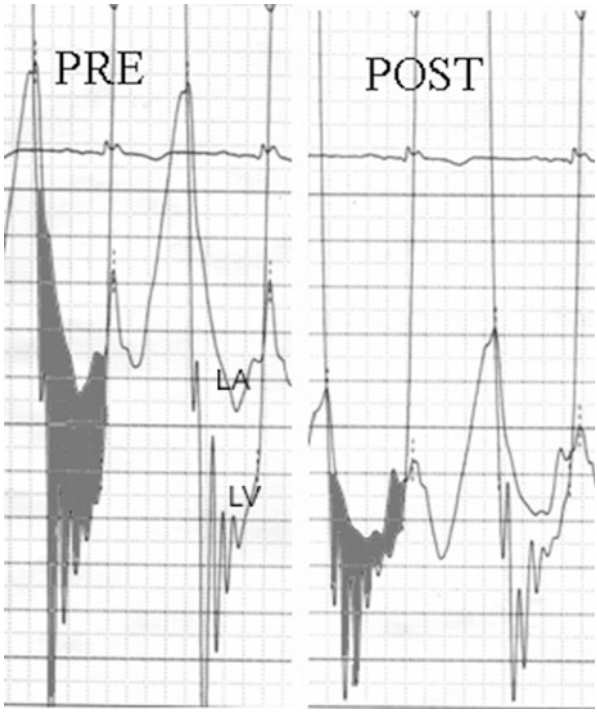

Fig. 33.4 Transmitral pressure gradient before and after BMV. The left panel shows a mean gradient of 16 mmHg (shaded area), representing the difference between the left atrial and left ventricular pressures. The valve area was 1.cm^2. After BMV the mean gradient has decreased to 6 mmHg, and the valve area has increased to 2.0 cm^2. *LA* left atrial pressure, *LV* left ventricular pressure

Complications

Major complications of BMV include worsening mitral regurgitation, which is seen in at least a minor degree in at least 15 % of patients [11]. Severe mitral regurgitation necessitating mitral valve replacement during the same hospitalization occurs in 2–4 % of patients. Hospital mortality is typically less then 1 %. TIA or stroke also occurs in less than 1 % of patients. Transseptal puncture is necessary to accomplish the procedure using antegrade approaches, and cardiac perforation occurs in one half percent to one and one-half percent of patients. Atrial septal defect complicating the transseptal puncture with a significant clinical shunt occurs in less than 2 % of patients.

Clinical Vignettes

Case 1

A 33 year old Asian woman presents in the 5th month of pregnancy with dyspnea at rest. A murmur is noted, and echo shows mitral stenosis with a transmitral gradient of 20 mmHg, pliable non-calcified leaflets, and no regurgitation. The valve area is 0.6 cm^2*. TEE shows no left atrial appendage thrombus*.

Once on the catheterization table, right femoral 14 F venous access is obtained. To minimize x-ray exposure, transthoracic echo is used during the procedure to monitor the valve gradient and regurgitation, rather than using hemodynamic measurements. Transseptal puncture is performed. The atrial septum is dilated and the Inoue balloon placed in the left atrium, then maneuvered into the left ventricle. The balloon is inflated partially, pulled back against the stenotic valve, and fully inflated. Echo shows no mitral regurgitation, but the gradient has only decreased to 12 mmHg and the valve area is 0.8 cm^2. A second inflation using a larger inflation volume (and therefore a larger inflated diameter) is performed, with resultant mild mitral regurgitation and a valve area of 1.9 cm^2. The sheaths are removed and after 6 h bedrest the patient is ambulated. She is discharged the next morning.

Case 2

A 157 cm tall, 54 year old woman presents with a history of slowly increasing dyspnea on exertion. She has a history of rheumatic mitral stenosis, and the valve area has decreased from 1.6 cm^2 *2 years ago to 1.2 cm*^{2} *on a recent echo exam. The is mild mitral regurgitation. TEE shows no left atrial thrombus, and coronary angiography shows no disease*.

Bilateral femoral access is obtained, with left arterial 6 F access for pressure monitoring and ventriculography, left 8 F venous access for right heart catheterization and

cardiac output measurement, and 14 F right venous for transseptal puncture and passage of the BMV balloon. After transseptal access, atrial septal dilatation, and passage of the balloon into the left atrium and then left ventricle a first inflation is performed. Initial balloon inflation diameter is estimated from patient height using the empiric formula (height in cm/10)/10 = expected inflation diameter. In this case the expected inflation diameter is 26 mm, so a first inflation of 24 mm is used. This results in no change in the LA pressure or mitral gradient. A second balloon inflation to 25 mm has similar results, but after the 3rd inflation to 26 mm balloon diameter the mean gradient decreases to 7 mmHg and the valve area increase to 2.1 cm^2. Repeat left ventriculography shows no change in the mild mitral regurgitation. The sheaths are removed and the patient ambulated after 6 h, She is discharged the next morning.

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Chapter 34
Transcatheter Aortic Valve Replacement

Jason B. Coker, James N. Hadstate, Andrew R. Weintraub, and Daniel H. Steinberg

Aortic stenosis is the most common valvular pathology in the developed world. The natural history of aortic stenosis is well established. For patients with severe aortic stenosis (jet velocity >4 m/s, mean gradient >40 mmHg, valve area <1 cm^2), the cardinal symptoms of cardiac syncope, angina, or exertional dyspnea portend a very poor prognosis with medical treatment alone. As such, The American College of Cardiology/American Heart Association guidelines recommend surgical aortic valve replacement for patients with severe, symptomatic aortic stenosis [1].

Surgical valve replacement has been the standard of care for the overwhelming majority of patients with symptomatic, severe aortic stenosis. However, many patients, particularly those of advanced age, have comorbid conditions resulting in elevated or prohibitive surgical risk. Unfortunately, for patients at prohibitive surgical risk, medical therapy does little to alter the natural course of disease. The advent of transcatheter technologies has ushered in a new era in the treatment of valvular heart disease.

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Indications

Appropriate patient evaluation is of paramount importance. The American College of Cardiology/American Heart Association guidelines recommend the use of a heart valve team in patients for whom transcatheter aortic valve replacement (TAVR) or high-risk surgical valve replacement is being considered [1]. A heart valve team typically consists of an integrated, multidisciplinary group of healthcare professionals with expertise in valvular heart disease, cardiac imaging, interventional cardiology, cardiac anesthesia, and cardiac surgery [2]. Along with the heart valve team, there are several objective risk stratification tools currently available to quantify risk and assist in patient selection for TAVR. The two most commonly used risk tools are the Society of Thoracic Surgery (STS) and the EuroSCORE.

On the basis of pivotal trials in elevated and extreme risk patients, TAVR is currently approved for patients deemed at elevated surgical risk as determined by a heart valve team [1–4]. This determination typically involves either an STS score predicted mortality of >8 % or 2 or more frailty criteria. Recently published studies examined current and recent generation transcatheter systems in intermediate risk patients defined as an STS score predicted mortality of 4–8 % or 1 frailty criterion with encouraging results [5, 6]. Indications for TAVR in intermediate risk patients may be expanded in the future. Randomized studies for patients at low risk for surgical valve replacement are currently enrolling.

Contraindications

Absolute contraindications for TAVR implantation are limited to patients who have less than 1 year life expectancy for reasons other than aortic stenosis. Relative contraindications for TAVR implantation are largely anatomic in nature. Inadequate coronary heights or a narrow sinus of Valsalva may be considered relative contraindications as the implantation of the TAVR can push that native valve leaflets backwards and potentially obstruct coronary arteries with a low take-off. This can be overcome by protecting coronary arteries with wires and undeployed coronary stents that can then be deployed if there is evidence of coronary obstruction.

Equipment

In the United States, two transcatheter technologies are currently available for commercial use, the balloon expandable Sapien S3 Valve (Edwards Life Sciences, Irvine CA) (Fig. 34.1) and the self-expanding CoreValve Evolut R (Medtronic, Minneapolis, MD) (Fig. 34.2). The S3 platform is available in 20, 23, 26 and 29 mm sizes delivered through a specially- designed 14 French sheath (the 29 mm device requires a 16 French sheath). The Evolut platform is available in 23, 26, 29 and 31 mm sizes

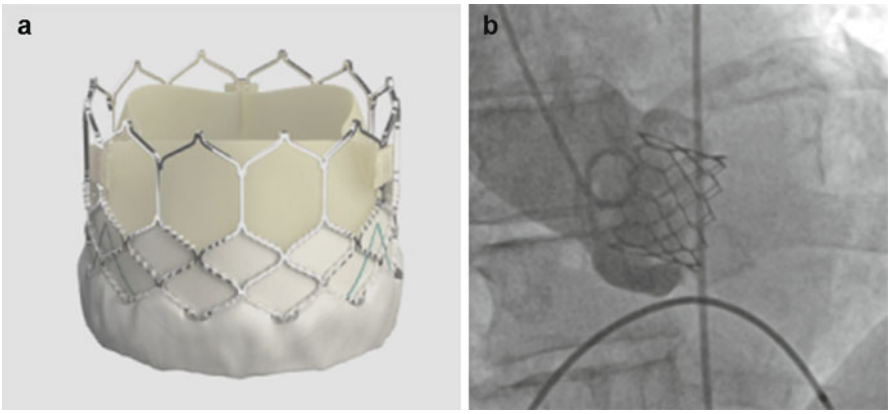

Fig. 34.1 (**a**) Balloon expandable Edwards Sapien three valve (**b**) Fluoroscopic image of deployed Edwards Sapien three valve

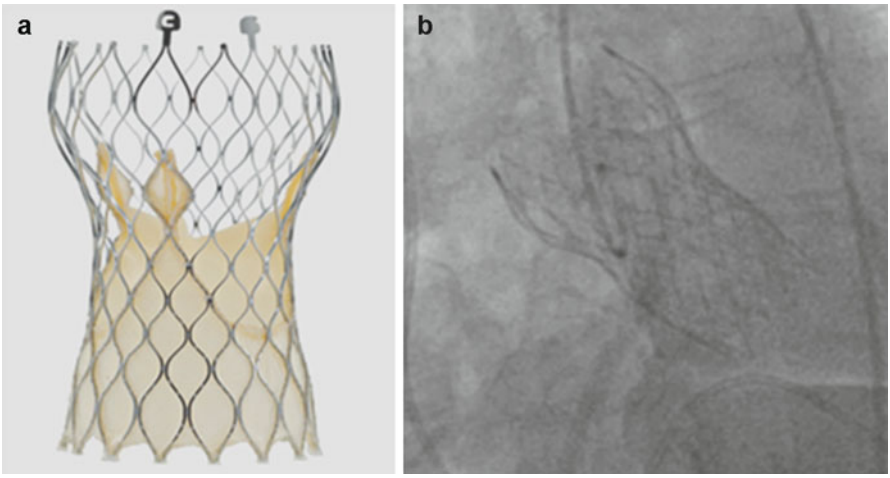

Fig. 34.2 (**a**) Medtronic Evolut R CoreValve (**b**) Fluoroscopic image of deployed medtronic Evolut R CoreValve

typically delivered via an in-line 14 French sheath (the 31 mm device requires an 18 French sheath). Equipment used in our current practice is summarized in Table 34.1.

Techniques

Current ACC/AHA guidelines recommend the use of a hybrid operating theatre for implantation of the transcatheter aortic valve, although at some centers, there has been a transition to procedural performance in appropriately outfitted

Table 34.1 Procedural equipment

	Equipment	Comments
Basic essentials	Hybrid suite	Capable of full catheterization and surgical needs
	Anesthesia setup	General or conscious sedation
	Surgical setup	
	Perfusion pump	Not necessarily primed, but available
	Transvenous pacemaker	
	Transesophageal echocardiography	As appropriate, not necessary for all cases
	PCI equipment	Standard guides, wires, stents available
	Covered stents	Available for vascular complication
Sheaths	Standard access equipment	May require longer sheaths
	Specialty sheath	Multiple types available – based on specific procedure and access site
Catheters	JR4, AL1	For crossing valve (others as appropriate)
	2 Pigtail catheters	For exchange, aortography and hemodynamic evaluation
Wires	0.035″ angiographic	Both 150″ and 260″
	0.035″ straight tip	For crossing – we prefer hydrophilic wire
	0.035″ extra/super stiff	Depends on valve type, dedicated pre-curved wires available
Specialty	Valvuloplasty balloon	Size chosen by purpose (i.e. priming, sizing,)
	Transcatheter valve	As appropriate

catheterization laboratories. Current guidelines also mandate that both an interventional cardiologist and cardiothoracic surgeon be present for the procedure [1].

The preoperative evaluation is summarized in Fig. 34.3, and it is essentially congruent with a surgical evaluation with the addition of Multidetector Computed Tomography (MDCT). This modality is of particular importance for TAVR as it enables one to choose the appropriate device size based on aortic annular area/perimeter, evaluate left ventricular outflow tract and valvular calcification, assess coronary heights, sinus width, sinotubular junction diameters/calcification, angiographic views and potential access routes (Fig. 34.4). While many of these variables can be assessed through alternative modalities, MDCT is a singular, detailed and three-dimensional modality with dedicated software systems allowing for reliable and reproducible analyses and pre-TAVR planning.

Regarding access, the transfemoral route is generally favored for patients with suitable iliofemoral anatomy to accommodate currently available devices, and approximately 80 % of procedures are now performed via transfemoral access. For patients with iliofemoral disease precluding device delivery, alternative access routes are possible. These alternative sites include open iliac (via conduit), subclavian, direct aortic or transapical. Additionally, direct carotid or transcaval access (with crossover from the inferior vena cava to the aorta) may be of utility in appropriately selected patients.

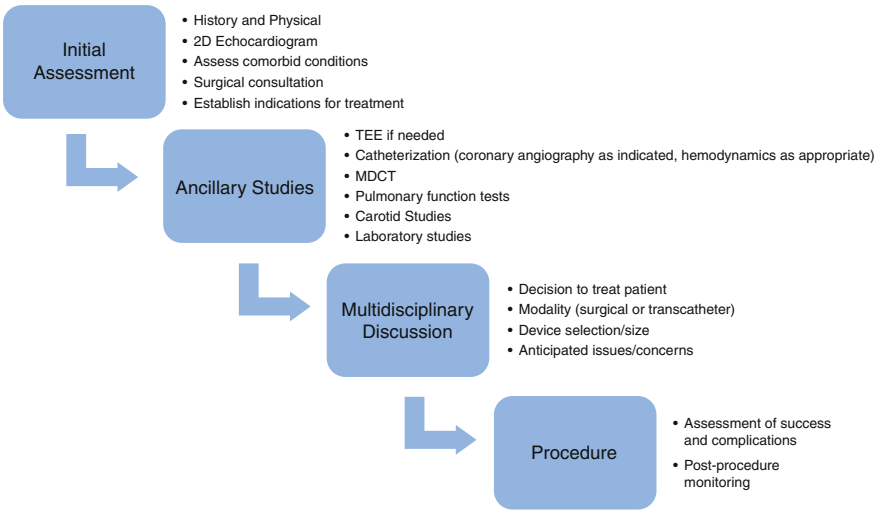

Fig. 34.3 Procedural evaluation

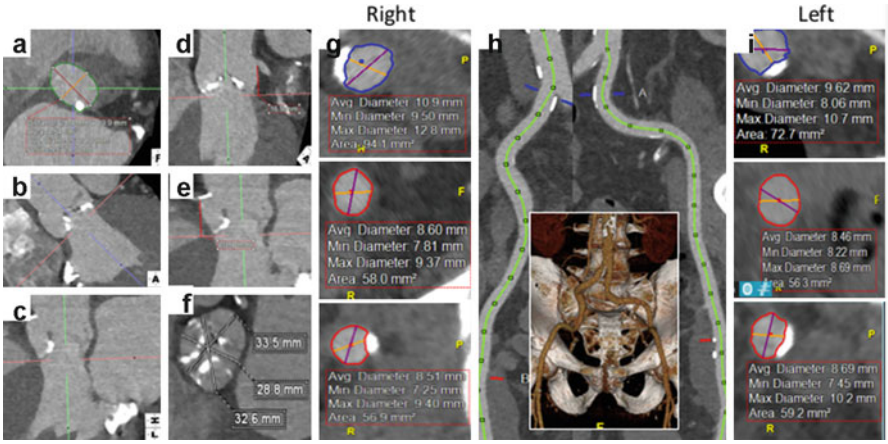

Fig. 34.4 MDCT assessment. (**a**) Annulus measurement. (**b**) Coronal angle at level of annulus. (**c**) Sagittal angle at level of annulus. (**d**) Left coronary height. (**e**) Right coronary height. (**f**) Sinus of Valsava measurements. (**g**) Right iliofemoral minimums. (**h**) Iliofemoral scout. (**i**) Left iliofemoral minimums

Typical procedural steps for each device are outlined here and described in the clinical vignettes below. Regardless of the planned primary access site, additional arterial access is obtained for annular assessment and venous access is obtained for delivery of a transvenous temporary pacemaker. A pigtail catheter is advanced to the aortic root and aortography is then performed to identify the annular plane. The aortic valve is crossed with a straight wire using a JR4 or AL1 coronary catheter,

and a second pigtail is exchanged for measurement of simultaneous left ventricle-aortic pressure gradient. A stiff 0.035″ wire is then advanced into the left ventricle. Priming valvuloplasty is typically preformed under conditions of rapid pacing. Following priming valvuloplasty, the valve is placed across the aortic valve with appropriate position confirmed by aortography prior to valve deployment.

The valves are deployed via respective techniques (described in the vignettes below). Hemodynamic assessment is performed with simultaneous left ventricle-aortic pressure measurements to assess post implantation gradient and aortic insufficiency. Positioning and aortic insufficiency is also assessed through aortography and echocardiography as indicated. Post dilation is performed as needed, usually to address perivalvular regurgitation. Access site management/closure is performed based on the chosen access site. In patients undergoing balloon expandable valve implantation, the pacing wire can be removed if there is no evidence of conduction disturbance, while for those receiving a self-expanding valve, the temporary pacing wire should remain in place up to 48 h prior to removal given the enhanced risk of conduction disturbances with these devices.

Data Interpretation

After valve implantation the operator must assess multiple factors before the procedure is considered successful. Immediate attention is given to the acute hemodynamics and recovery of systemic pressures. The ECG is examined for conduction disturbances and/or ST changes suggestive of coronary occlusion. Once stable, the post implantation pressure gradient is directly measured via catheters in the left ventricle and aortic root followed by an assessment of aortic insufficiency and coronary patency by aortic root angiography. A transvalvular gradient of <10 mmHg is expected in the majority of cases, and an increased gradient should lead to re-evaluation of the valve for complete expansion.

While trace to mild residual aortic insufficiency is generally acceptable, greater than moderate aortic regurgitation after implantation has been shown to predict long term mortality throughout TAVR trials. Aortic insufficiency is visually assessed by aortography and clinically assessed via assessment of diastolic pressure separation. More than mild-moderate AI should lead to re-evaluation of valve expansion and deployment location for potential remedies such as post dilation or implantation of a second valve.

Complications

For purposes of data collection and consistency, complications have been precisely defined by the Academic Research Consortium and are reported in the Transcatheter Valve Technologies registry (a requirement for reimbursement in the United States)

[7]. Procedural success is defined as successful vascular access and appropriate placement of a single valve with less than moderate aortic insufficiency. With increased global experience and device iteration, procedural success approaches 95–100 %, and overall complication rates continue to improve with intraprocedural mortality generally less than 1 % and in-hospital mortality less than 5 %. Major acute complications include annular rupture, ventricular perforation, acute aortic insufficiency, coronary obstruction, complete heart block and vascular compromise. These complications often manifest with acute hemodynamic, electrocardiographic or echocardiographic changes. Treatment depends on the cause and temporizing resuscitative measures are often employed while the underlying issue is addressed.

In the post-operative period, the more important complications following TAVR include clinically evident stroke in about 3–5 % of cases and conduction disturbances requiring permanent pacemaker implantation in up to 20 % of cases depending on the particular valve used. Conduction abnormalities following TAVR are related to the close proximity of the aortic annulus and specialized conduction tissue, and these are more common with self-expanding valves compared to balloon expandable devices. Rates of complete heart block also appear dependent on the depth of implantation relative to the annulus [7].

Clinical Vignette 1

Case #1

A 79 year old male with hypertension, hyperlipidemia, diabetes on oral medications, moderate lung disease, chronic renal insufficiency, coronary artery disease with prior CABG, chronic diastolic heart failure and severe aortic stenosis presented for evaluation. Symptoms were consistent with New York Heart Association Class 3, and after multidisciplinary evaluation, he was considered at elevated risk for surgical AVR with an STS predicted risk of mortality of 8.4 %. Physical exam was consistent with severe aortic stenosis. Echocardiogram demonstrated an ejection fraction of 60 %, annular diameter 21 mm, aortic valve area of 0.8 cm^2, peak velocity 4.2 m/s and mean gradient 43 mmHg with trace aortic insufficiency. Coronary artery angiography demonstrated multivessel coronary disease with patent grafts. CTA of the chest, abdomen and pelvis revealed a trileaflet aortic valve, a calcium score 6348, annular area 470 mm^2, annular-coronary heights greater than 10 mm bilaterally, and iliofemoral minimal diameters of 6.6 mm at the left common femoral artery, and 6.2 mm at the right common femoral artery.

Percutaneous access was obtained on the right common femoral artery. Contralateral arterial and venous access was obtained percutaneously. The right common femoral artery was "preclosed" with 2 suture devices, and using standard techniques, a 14 French hemostatic sheath was secured in place. The aortic valve was crossed with a 0.038″ straight-tipped Glidewire and a JR4 catheter. A 0.035″ extra stiff wire was advanced into the ventricle. A priming valvuloplasty was per-

formed with a 23 mm×4 cm balloon under rapid pacing. With rapid pacing and under both fluoroscopic and aortographic guidance, the valve was deployed. After full deployment, rapid pacing was ceased. Valve positioning and aortic insufficiency was assessed by aortography and hemodynamics. All equipment was removed, and percutaneous closure commenced. Completion angiography was performed with no complications noted.

The patient improved post procedure and was discharged 48 h post TAVR implant. Predischarge echocardiography demonstrated normal LV systolic function with a mean gradient across the aortic prosthetic valve of 16 mmHg with trace paravalvular regurgitation.

Case #2

A 77 year old frail female with hypertension, hyperlipidemia, diabetes on oral medications, mild lung disease, chronic renal insufficiency, chronic diastolic heart failure and severe aortic stenosis presented for evaluation. Symptoms were consistent with New York Heart Association Class 3 congestive heart failure, and after multidisciplinary evaluation, she was considered at elevated risk for surgical AVR with an STS predicted risk of mortality of 9.3 %. Physical exam was consistent with severe aortic stenosis. Echocardiogram demonstrated an ejection fraction of 50 %, annular diameter 20 mm, aortic valve area of 0.7 cm^2, peak velocity 4.0 m/s and mean gradient 40 mmHg with mild aortic insufficiency. Coronary artery angiography demonstrated insignificant coronary disease. CTA of the chest, abdomen and pelvis revealed a trileaflet aortic valve, a calcium score 1555, aortic annular area 380 mm^2 and perimeter 68.7 mm, annular-coronary heights greater than 10 mm bilaterally, and iliofemoral minimums of 6.4 mm at the left common femoral artery, and 6.2 mm at the right common femoral artery.

Percutaneous access was obtained on the right common femoral artery. Contralateral arterial and venous access was obtained percutaneously. A 6 F sheath was inserted in the contralateral femoral artery, and a 5 French pigtail catheter was placed via through the sheath in the ascending aorta. A transvenous pacemaker wire was placed via the right internal jugular vein. Pacing thresholds were optimized, and proper alignment of the aortic cusps was determined via aortography. The right common femoral artery was "preclosed" with two suture devices, and a 14 F hemostatic sheath was secured in place via standard techniques. Anticoagulation was initiated with unfractionated heparin. The aortic valve was crossed with a 0.038″ straight-tipped Glidewire and a JR4 catheter. A soft 0.035″ exchange length wire was advanced into the ventricle via the JR4, and a 6 F pigtail catheter was exchanged over the wire. Simultaneous pressures were recorded. A 0.035″ super stiff exchange length wire was advanced into the ventricle.

Under conditions of rapid pacing, a priming valvuloplasty was performed with a 20 mm×4 cm balloon, which was then removed. The sheath was exchanged over the super stiff wire for the in-line 14 F system. A 26 mm self-expanding CoreValve

Evolut R was loaded onto the delivery catheter and advanced over the exchange wire into position across the aortic valve. Under fluoroscopic, aortographic and echocardiographic guidance, the valve was positioned precisely across the aortic valve, and deployment commenced. Once annular contact was achieved, accelerated pacing was started, and the valve was unsheathed further. After 2/3 deployment, pacing was ceased. Valve positioning and aortic insufficiency was assessed by echocardiography and aortography. The valve was fully deployed and detached, the delivery catheter was removed, and the pigtail catheter was advanced over the exchange wire for hemodynamic, echocardiographic and aortographic assessment. The pigtail was then removed.

The second pigtail catheter was placed into the descending aorta, and pacemaker wire was kept in place. The delivery sheath was retracted, and percutaneous closure commenced. A completion angiogram was performed. No complications were noted, and all other equipment was removed.

The patient improved post procedure and was discharged 72 h post TAVR implant. Predischarge echocardiogram demonstrated normal LV systolic function with a mean gradient across the aortic prosthetic valve of 10 mmHg with trace paravalvular regurgitation.

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Chapter 35
Endomyocardial Biopsy

Johny Kuttab and Carey Kimmelstiel

Endomyocardial biopsy is an invasive procedure performed by interventional cardiologists. The procedure is widely used to screen and survey transplanted hearts for signs of cellular or humoral rejection allowing for titration of immunosuppressive therapy. Although this remains the strongest indication for the procedure [1–3], its clinical utility could be expanded to the diagnosis of other myocardial processes.

Indications

In general, the use of EMB is recommended in clinical scenarios in which the diagnostic yield of the procedure outweighs the procedural risk.

The following are indications for EMB [3]:

1. Surveillance for cardiac allograft rejection remains the most important indication for EMB.
2. Fulminant heart failure with hemodynamic compromise. The prototype for this group of patients is lymphocytic myocardidites, eosinophilic myocarditis or giant cell myocarditis.
3. New-onset heart failure associated with high degree atrioventricular (AV) block or ventricular arrhythmias. These clinical manifestations could be suggestive of giant cell myocarditis in which case tissue diagnosis is important for treatment and prognosis.

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4. Chronic heart failure with high degree AV block or ventricular arrhythmias which could be suggestive of cardiac sarcoidosis.
5. Unexplained restrictive cardiomyopathy. Cardiac amyloidosis and hemochromatosis are diagnoses that fall within this group of infiltrative cardiomyopathies.
6. Hypereosinophilic syndrome and endomyocardial firboelastosis.
7. The workup of cardiac tumors.
8. The monitoring of anthracycline cardiotoxicity.
9. Unexplained cardiomyopathy in children.
10. The diagnosis of arrhythmogenic right ventricular cardiomyopathy when other noninvasive or invasive modalities are inconclusive.

Contraindications

There are no absolute contraindications for EBM. Relative contraindications include [3]:

1. Coagulopathy.
2. Hemodynamic compromise or active heart failure precluding patient positioning and sedation.
3. Pericardial effusion or tamponade.

Equipment

1. Central venous access kit and sheath: Sheath size depends on the type of bioptome used.
2. Bioptome: There are various types of bioptomes. In general, two types of bioptomes – those with a floppy shaft which requires the use of a long sheath for delivery and the more commonly used stiff shaft which is manipulated into the region being biopsied (usually the right ventricle) after being introduced, via a short sheath, located within a central vein.
3. Ultrasound (echocardiography) machine: Most EMBs are performed using fluoroscopic imaging for bioptome positioning. Occasionally, when a specific region of the heart requires biopsy, echocardiography may be necessary to guide the bioptome to that area of the heart. In addition, echocardiography is frequently used to guide EMB in those instances where the risk of right ventricular perforation is elevated. Examples of this clinical scenario include patients with fulminant myocarditis eg. giant cell myocarditis where the combination of the thin-walled right ventricle and a closed pericardium lead to a heightened risk of myocardial perforation and subsequent cardiac tamponade. In such cases, echocardiography is frequently used to ensure that the bioptome is pointed toward the interventricular septum as opposed to the right ventricular free wall (Fig. 35.1).

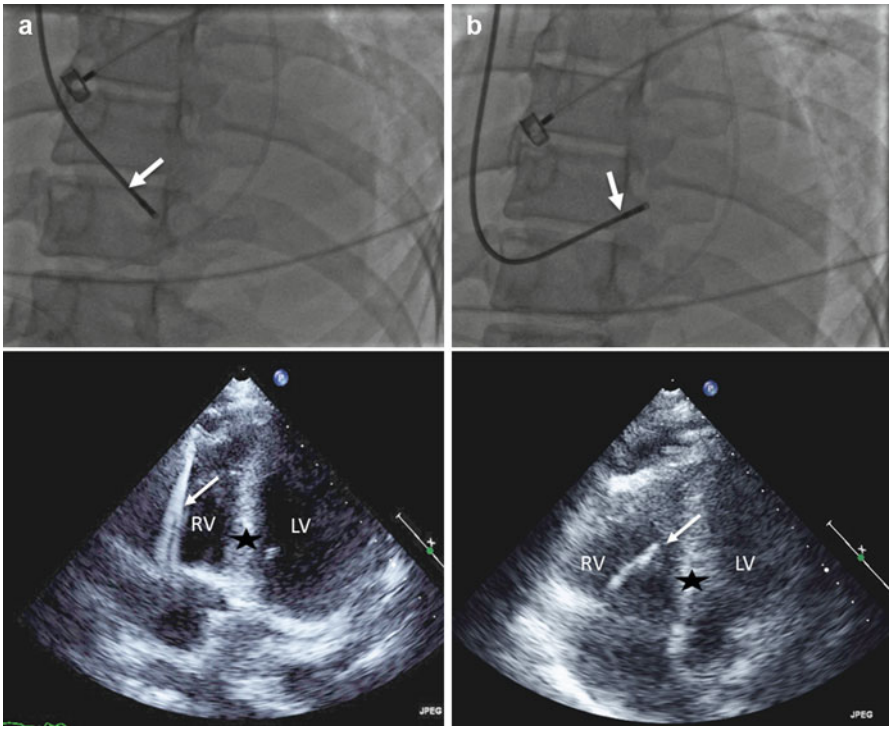

Fig. 35.1 Panel (**a**) Fluoroscopic view (*top*) of bioptome (*arrow*) in an incorrect position. Echocardiography (*bottom*) documents that the tip of the bioptome (*arrow*) is positioned against the right ventricular free wall, near the apex – a position putting the patient at risk for perforation if biopsied there. Panel (**b**) Fluoroscopy shows that the bioptome (*arrow*) has been repositioned to a more appropriate location, pointing superior and posterior (*top*). Echocardiography (*bottom*) documents that the bioptome (*arrow*) is pointing towards the interventricular septum (*star*)

Technique

There are three commonly utilized access sites for EMB. The most commonly used route is the right internal jugular vein. In this technique, the patient is prepped and draped in a sterile fashion. Ultrasonography, although not absolutely necessary, is commonly utilized for obtaining access to the vein. The venous sheath is then inserted over a wire. Once the sheath is flushed, the bioptome is inserted through the venous sheath under fluoroscopic guidance and advanced superiorly and posteriorly towards the interventricular septum. Once positioning is verified, the bioptome jaws are opened (Fig. 35.2), advanced towards the septum, and closed. The bioptome is pulled back gently at this time. Once the bioptome is free, it is pulled out of the venous sheath and the biopsied tissue is removed from the forceps and the procedure is repeated over again. Occasionally,

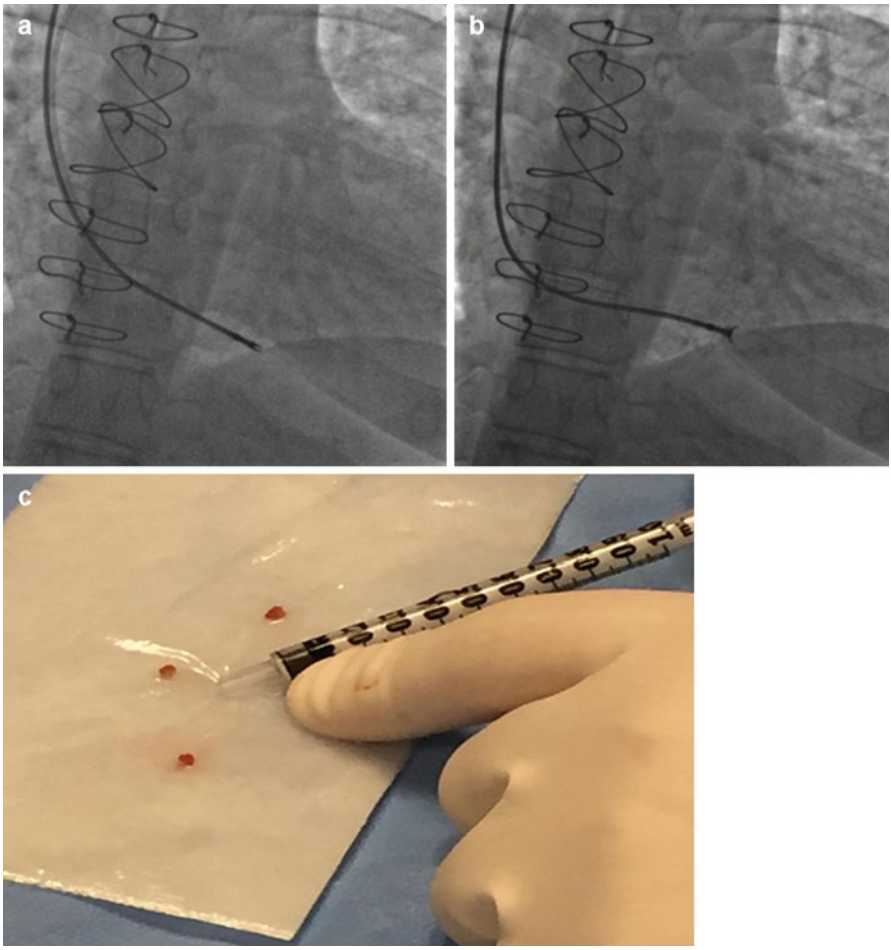

Fig. 35.2 (**a**) A bioptome, in the closed position, which has coursed from the right internal jugular vein through the right atrium, into the right ventricle. (**b**) The bioptome is in the open position as the interventricular septum is biopsied. (**c**) Three biopsies of myocardial tissue obtained during the procedure

echocardiographic guidance may be utilized to assist in bioptome positioning while performing EMB.

Other commonly used access sites include the subclavian/axillary vein and the femoral venous approach. When the femoral vein is used, a longer bioptome is used (105 cm) which is introduced through a long 7F venous sheath. Internal jugular and subclavian approaches utilize the standard 50 cm bioptome introduced through a standard 7F 11 cm long venous sheath.

In rare instances, the femoral arteries could be utilized for EMB of the left ventricle.

Data Interpretation

Storage of the sample is dictated by the clinical question to be answered. A minimum of 5 right ventricular samples should be obtained if possible. Standard histological preparation using paraffin embedding, sectioning and staining can be used in the diagnosis of allograft rejection, myocarditis or amyloidosis. Polymerase chain reaction for the detection of viruses can be performed on paraffin-embedded tissue although the sensitivity is higher when performed on liquid nitrogen frozen tissue.

Complications

The rate of complications during an EMB depends on multiple factors. It is reported to be <6 % in most case series. The following are possible complications [1–3]:

1. Access site hematoma.
2. Supraventricular and ventricular arrhythmias
3. Transient right bundle branch block.
4. Tricuspid regurgitation.
5. Air embolism
6. Occult pulmonary embolism
7. Vein thrombosis.
8. Pneumothorax.
9. Bleeding.
10. Right ventricular perforation.
11. Pericardial effusion with tamponade physiology.
12. Death.

Clinical Vignettes

Case 1

A 58 year old female patient, presented to the Advanced Heart Failure and Transplant clinic with progressively worsening dyspnea on exertion, lower extremity edema, orthopnea, paroxysmal nocturnal dyspnea and cough. She was initially treated at a community hospital for possible flu, however she experienced a progressive clinical decline. Her initial echocardiographic assessment revealed an ejection fraction of 30 %, with left ventricular hypertrophy, bi-atrial enlargement, and Doppler parameters consistent with stage III diastolic dysfunction. On initial assessment, she was found to have elevated levels of serum free light chains. A cardiac MRI was pursued at that time and was significant for multifocal thickening of

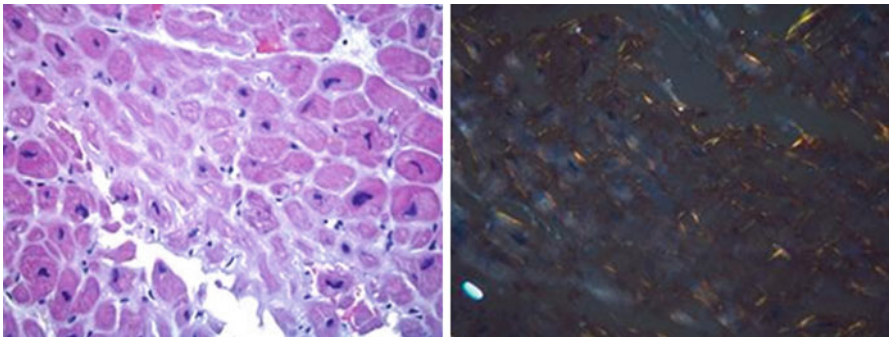

Fig. 35.3 *Left* – Endomyocardial biopsy from the patient in Case 1. Amyloid deposits appear as light-pink hyaline extracellular deposits displacing cardiac myocytes. *Right* – Congo red staining of the biopsy sample shows apple-green birefringence of the amyloid deposits

the myocardium with sparing of the anterior wall, multifocal delayed transmural hyperenhancement with relative sparing of the anterior wall, and diffusely decreased T1 signal, findings consistent with amyloidosis. Shortly after, she underwent a fat pad biopsy to look for evidence of systemic amyloid. Unfortunately this was non-diagnostic. An endomyocardial biopsy was ultimately done. Histological findings (Fig. 35.3) *were diagnostic for cardiac amyloidosis.*

Case 2

A 57 year old man with a history of familial hypercholesterolemia, complicated by coronary artery disease requiring multiple coronary artery bypass surgery developed worsening heart failure secondary to ischemic cardiomyopathy despite optimal heart failure medications, necessitating an orthotopic heart transplantation. His immediate post-transplant course was uneventful. Six months following transplant, he presented with new onset cardiogenic shock, a newly depressed ejection fraction and refractory ventricular tachycardia. He underwent a right heart catheterization with an endomyocardial biopsy which was significant for high grade cellular rejection. Based on the biopsy results, he underwent treatment with thymoglobulin and high dose intravenous steroids with stabilization of his clinical status.

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Chapter 36
Circulatory Support Devices

Navin K. Kapur and Michele Esposito

Introduction

The role of percutaneously-delivered mechanical circulatory support (pMCS) devices in the cardiac catheterization lab has been expanding over the last decade. Current pMCS options include the intra-aortic balloon pump (IABP), Impella axial flow catheter, TandemHeart centrifugal pump, and veno-arterial extracorporeal membrane oxygenation (VA-ECMO). The overall goals of pMCS systems are to: (1) increase vital organ perfusion, (2) augment coronary blood flow, and (3) reduce ventricular volume and filling pressures, thereby reducing wall stress, stroke work, and myocardial oxygen consumption. Clinical scenarios where these devices are commonly used include: advanced heart failure, cardiogenic shock, mechanical complications after AMI, high risk coronary and non-coronary intervention, and high-risk electrophysiologic ablations.

Intra-aortic Balloon Counterpulsation

The hemodynamic effects of IABP counterpulsation work to improve the myocardial supply and demand balance. Rapid expansion of the balloon in early diastole augments diastolic pressure and can increase coronary perfusion pressure. Rapid deflation at end-diastole decreases left ventricular (LV) afterload by driving aortic

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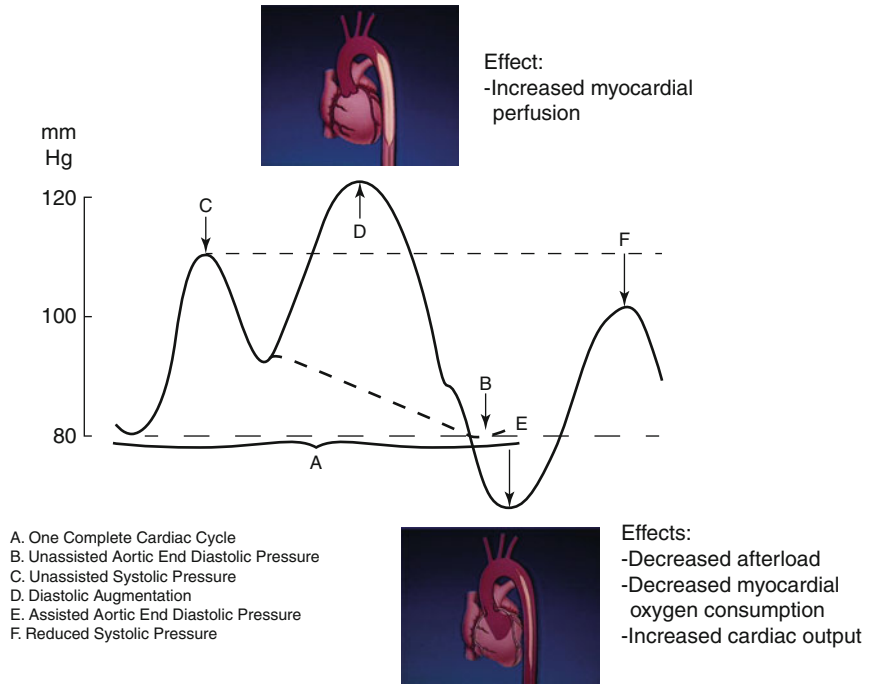

Fig. 36.1 The IABP improves the myocardial supply and demand balance by increasing myocardial perfusion during diastole and decreasing resistance to left ventricular ejection during systole (with permission from Datascope)

Table 36.1 Hemodynamic effects of the IABP

Systolic BP	Diastolic BP	MAP	HR	CO	PCWP
↓	↑	No change or ↑	↓	↑	↓

volume forward and reducing aortic pressure during systole (Fig. 36.1). Expected effects on the hemodynamic profile of patients with cardiogenic shock include an increase in the diastolic pressure; a decrease in the systolic pressure; an overall maintenance or slight improvement in the mean arterial pressure; a reduction in the heart rate; an elevation in the cardiac output; and a decrease in the pulmonary capillary wedge pressure (Table 36.1) [1].

Indications

Hemodynamic Compromise

Indications for IABP placement include patients with acute myocardial infarction (MI) and cardiogenic shock secondary to continued ischemia or myocardial stunning. Without revascularization, survival rates in patients with cardiogenic shock

supported with IABP and medical therapy are quite poor. The IABP provides temporary hemodynamic stabilization until definitive revascularization can be performed. The IABP might also be used to support patients with shock due to mechanical complications of MI—e.g. ventricular septal rupture – until corrective surgery can be performed. Additionally, it has been shown to be an effective temporary therapeutic option in patients with shock due to non-ischemic reversible causes, such as myocarditis or drug toxicity. IABP support is often used in patients who are difficult to wean off bypass after cardiac surgery due to severe LV dysfunction or secondary to myocardial stunning from prolonged cardioplegia. Patients with refractory heart failure and those with end-stage cardiomyopathy awaiting cardiac transplantation--i.e., "bridge to transplantation" -- might also gain benefit from IABP support. Furthermore, the IABP can contribute to the management of patients with medically intractable ventricular arrhythmias, including ventricular tachycardia and ventricular fibrillation [1, 2].

Absence of Hemodynamic Compromise

The IABP is often used to alleviate medically refractory unstable angina in patients awaiting definitive revascularization -- e.g., a patient with severe triple vessel coronary artery disease awaiting bypass surgery. Prophylactic placement is employed in patients with severe left main coronary obstruction or decompensated aortic stenosis awaiting surgery. The IABP might also be placed to mitigate continued ischemia following complex/complicated percutaneous coronary intervention (PCI) or to support patients with failed PCI. In addition, the prophylactic placement of IABP is occasionally employed during high-risk PCI [1]

Contraindications

Major contraindications to IABP placement include significant aortic regurgitation, abdominal or thoracic aortic aneurysm, aortic dissection, severe peripheral vascular disease (aorto-iliac or femoral artery disease), severe bleeding diathesis, and uncontrolled septicemia.

Equipment

The intra-aortic balloon pump consists of a polyurethane balloon, which surrounds a double lumen catheter that is mounted onto a flexible shaft and connected to a console. It is inflated by a helium gas control system, which is housed within the console.

Technique

Insertion

After the leg is shaved and prepped with anti-septic solution, the femoral artery is accessed and J-tipped guide wire is passed through a needle to the aortic arch. After an introducer sheath is inserted, the balloon is advanced over the guide wire with the radiopaque tip positioned in the descending aorta just distal to the origin of the left subclavian artery (generally at the level of the carina). When available, fluoroscopic guidance should always be employed for IABP placement. If fluoroscopic guidance is not available, the distance from the angle of Louis (or between the second and third intercostal spaces) to the umbilicus and then obliquely over to the femoral insertion site can be measured to determine the approximate distance the balloon should be advanced. After positioning of the IABP is confirmed, the helium gas line extending from the console is connected. Balloon counterpulsation is then initiated at 1:2 setting (balloon inflation with every other beat) and fluoroscopy again is used to confirm uniform expansion. Sheathless insertion is sometimes performed in patients with peripheral vascular disease in an attempt to reduce the incidence of lower limb ischemia. However, sheathless insertion does not allow for repositioning once the balloon is placed, and is associated with higher rates of infection [1].

Inflation and deflation of the balloon are usually timed and triggered by the surface electrocardiogram. Triggering can also be initiated by the arterial pressure waveform or set to a fixed asynchronous cycle for patients with significant arrhythmias—e.g., ventricular fibrillation – or patients on bypass. Pacing spikes should be used to trigger the balloon in patients with 100 % paced rhythms. Adjustments to timing are performed with initial pump triggering set at 1:2, thereby allowing comparison of the arterial tracing with and without counterpulsation (Fig. 36.2). Timing of inflation is delayed after the R wave on the surface ECG such as to begin on the downslope of the systolic pressure waveform, just before the dicrotic notch (when the aortic valve closes). Deflation should be timed just before the opening of the aortic valve to allow for the maximum reduction in aortic systolic pressure compared with an unassisted beat. After timing of inflation and deflation is adjusted, the balloon counterpulsation is then set at 1:1 (Fig. 36.3) [1].

Management of the Patient During Counterpulsation

When the patient is returned to the appropriate unit, a chest x-ray should be immediately obtained to again verify balloon position and check for any possible migration during transfer. To prevent thrombus formation, the patient is heparinized, the activated partial thromboplastin time being carefully maintained at 50–70 s. The patient must be kept at bedrest and the head of the bed should not be elevated more than 30°. Daily chest x-ray should be obtained to evaluate balloon position and

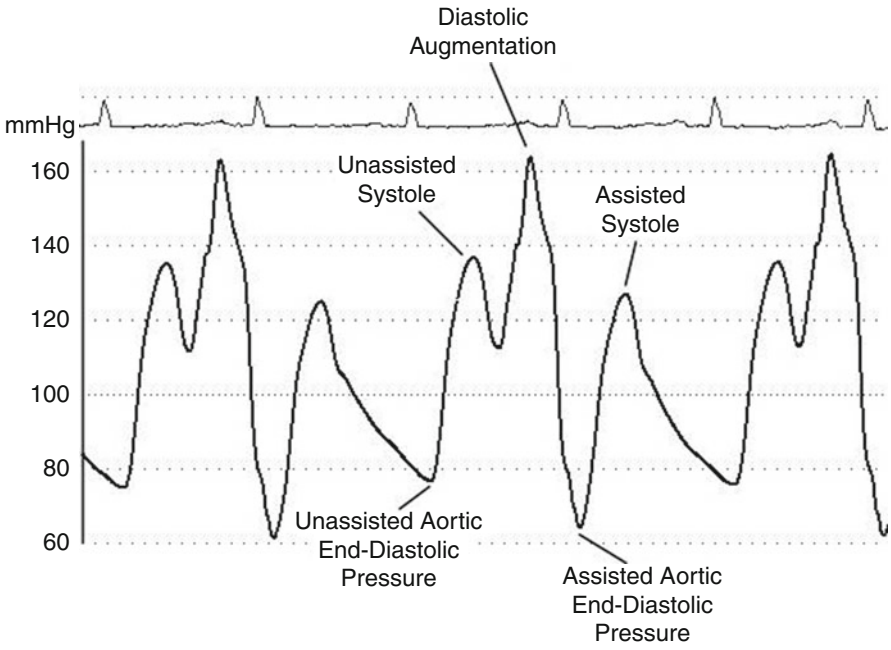

Fig. 36.2 Adjustment to timing is performed with the IABP set at 1:2 to allow comparison of the arterial tracing with and without counterpulsion. Timing of inflation is delayed after the R wave on the surface ECG such as to begin, just before the dicrotic notch on the aortic pressure waveform. Deflation is timed to allow for the maximum reduction in aortic systolic pressure compared with an unassisted beat

migration. During counterpulsation, evaluation of circulation should take place on every nursing shift (or at least Q8h). Daily monitoring for evidence of sepsis, bleeding, hemolysis, and embolus should also be performed [1].

Weaning from Counterpulsation

Before the IABP is removed, the patient is progressively weaned from its support. Under close hemodynamic supervision the counterpulsation mode is decreased stepwise from 1:1 to 1:2, and then to 1:3. The patient should be monitored for 2–3 h at each downgraded level to ensure tolerance to reduced support. When safety of withdrawal is established, the balloon is set back to 1:1 and the heparin drip is discontinued for at least 4 h. The activated clotting time is checked until it falls below 160 s. The balloon and sheath are then removed as a single unit to prevent any tearing of the balloon membrane. Manual pressure is then applied proximal to the insertion site for 30–60 min until hemostasis is achieved. After removal the patient is kept at strict bed rest avoiding hip flexion on the affected side for the next 6–12 h [1].

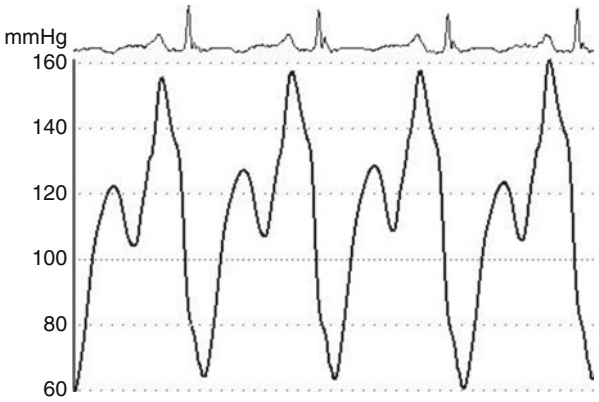

Fig. 36.3 IABP set at 1:1

Complications

Vascular complications remain the major risk associated with IABP placement. Among the significant vascular complications, the most common are limb ischemia, vascular laceration, and major hemorrhage. Other vascular complications include arterial dissection, pseudo-aneurysm formation, cholesterol embolization, and cerebrovascular accident (CVA). Risk of CVA increases if the IABP has been placed too high or has migrated proximally. Vigorous flushing of the central lumen should also be avoided, as it can result in dislodgement of thrombus. Overall, major complications (severe bleeding, major limb ischemia, balloon leak, or in-hospital mortality related to IABP) associated with IABP placement are relatively rare with an incidence of 2.6 % in the Benchmark Counterpulsation Outcomes Registry [1, 3].

Non-vascular complications include groin infection, sepsis (especially when counterpulsation is carried out for longer than a week), hemolysis, thrombocytopenia, and balloon rupture. Although rare, balloon rupture should be considered when blood is detected in the gas drive-line or if augmentation failure develops.

Clinical Vignettes

Case 1

A 65 year old woman with history of heavy tobacco use, HTN, and hypercholesterolemia presents to a community hospital emergency department (ED) with history of 3 days of intermittent chest pain and worsening shortness of breath. On arrival to the ED she is noted to be in respiratory distress secondary to pulmonary edema and is urgently intubated. ECG is consistent with inferior ST elevation myocardial infarction. Due to hypotension dopamine is initiated and she is taken emergently to the catheterization laboratory (cath lab). Coronary angiogram reveals three-vessel coronary artery disease with acute right coronary artery occlusion. Right heart

catheterization is performed and reveals right atrial (RA) pressure 12 mmHg, pulmonary artery (PA) pressure 64/29 (43) mmHg, and pulmonary capillary wedge pressure (PCWP) 33 mmHg with large V waves noted on the PCWP tracing (Fig. 36.4) *consistent with heart failure and severe mitral regurgitation. Transesophageal echocardiogram performed in the catheterization lab reveals papillary muscle rupture with severe new onset mitral regurgitation—a mechanical complication of acute myocardial infarction that can result in heart failure and cardiogenic shock.*

An intraarotic balloon pump is placed to stabilize the patient for transfer to a tertiary care center for coronary bypass surgery and mitral valve replacement.

Case 2

*A 77 year old male with history of diabetes and hypertension is admitted with unstable angina. Cardiac catheterization reveals triple vessel coronary artery disease with 80 % left main coronary artery stenosis, 90 % mid left anterior descending stenosis, 85 % proximal left circumflex stenosis, and 70 % mid right coronary stensosis. The patient is evaluated by cardiothoracic surgery and planned for CABG surgery in the morning. Chest pain free and hemodynamically stable, he is transferred to the coronary care unit for monitoring until surgery. Despite medical therapy with beta blockers, nitrates, and heparin the patient develops recurrent chest pain with ischemic ECG changes. He is returned to the cath lab for IABP placemen*t.

Case 3

A 59 year old male with history of severe ischemic cardiomyopathy (known ejection fraction of 15 %) is admitted with non-ST elevation myocardial infarction. He is taken emergently to the cardiac cath lab due to hypotension and persistent chest

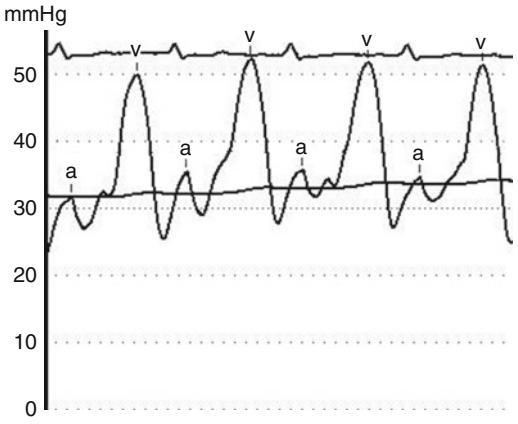

Fig. 36.4 PCWP profile in a patient with cardiogenic shock showing large V waves suggestive of severe mitral regurgitation. Echocardiogram revealed papillary muscle rupture complicating acute inferior myocardial infarction

pain. Cardiac catheterization reveals severe three-vessel coronary artery disease. Right heart catheterization reveals RA 8 mmHg, PA 49/24 (34) mmHg, PCWP 24 mmHg, and cardiac index of 1.14 L/min/M2 consistent with cardiogenic shock. The severe nature of his three-vessel coronary artery disease precludes percutaneous coronary intervention or bypass surgery.

IABP is placed and the patient is referred to the heart failure service for evaluation of heart transplantation. If the patient was not felt by the cardiology team to be a suitable candidate for heart transplantation (eg. due to old age or significant other medical comorbidities) placement of IABP would not be appropriate.

Continuous Flow Support Devices

The pMCS systems have grown from counterpulsation balloon systems to centrifugally driven circuits, or catheter-mounted axial-flow pumps. Both surgical LVADs and pMCS systems are subject to changes in preload and afterload. Inadequate LV preload due to volume depletion, poor right ventricular function, hypotension, pulmonary obstruction, or valvular disease will reduce flow generation. Similarly, increased afterload due to hypertension, elevated systemic vascular resistance or valvular disease will reduce device flow. For these reasons, careful hemodynamic interrogation before, during, and after initiation of pMCS is essential for optimal device function. Percutaneous circulatory support devices can be categorized by the type of pump used as either pulsatile or continuous blood flow devices. Each device impacts native ventricular function in a unique way and requires adequate preload for optimal use.

Both the Impella (Abiomed Inc) and TandemHeart (CardiacAssist Inc) devices are rotodynamic pumps that generate continuous, minimally pulsatile blood flow when functioning optimally (Fig. 36.5) [4, 5]. The Impella devices are catheter-mounted axial-flow pumps that are placed into the left ventricle in retrograde fashion across the aortic valve. The pump transfers kinetic energy from a circulating impeller to the blood stream, which results in continuous blood flow from the left ventricle to ascending aorta. The Impella 2.5 LP and CP devices can be deployed without the need for surgery, while the Impella 5.0 device requires surgical vascular access [4, 5]. At present, there is growing experience with the CP device in the United States. In contrast, the TandemHeart device is an extra-corporeal centrifugal flow pump that reduces left ventricular *preload* by transferring oxygenated blood from the left atrium to the descending aorta via two cannulas: a trans-septal inflow cannula in the left atrium and an arterial outflow cannula in the femoral artery. The net effect of these devices is to reduce native left ventricular volume and pressure, while increasing mean arterial pressure without greatly influencing ventricular afterload [6]. Advantages of the Impella 2.5 and CP devices is ease of insertion via a single arterial access, while an advantage of the TandemHeart device is the magnitude of support provided without the need for surgical vascular access. No studies comparing these continuous flow devices head-to-head exist.

Other centrifugal pumps include the Centrimag, Rotaflow, and Biomedicus pumps, which are more commonly implanted surgically or used to provide flow for

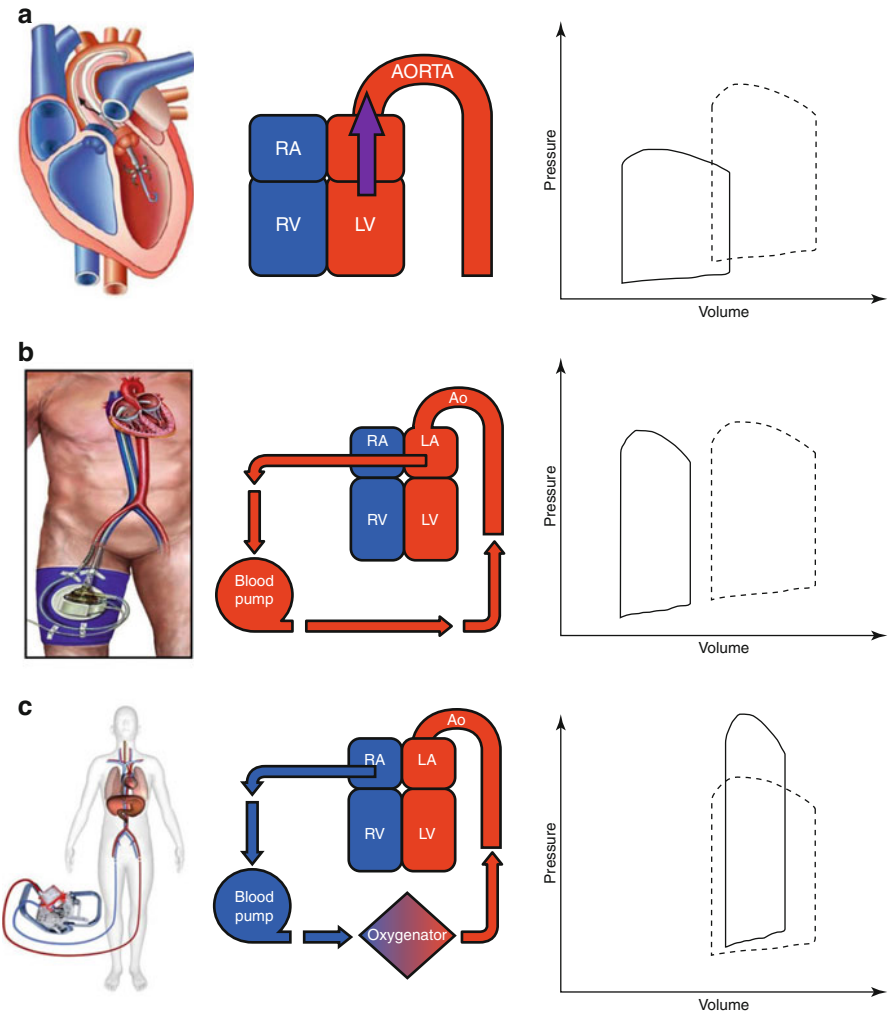

Fig. 36.5 Percutaneous non-durable mechanical circulatory support systems. (**a**) The Impella axial flow catheters are deployed in retrograde fashion across the aortic valve and directly displace blood from the LV into the proximal aorta. Immediate effects of the Impella activation include reduced left ventricular pressures and volume as shown by pressure-volume (PV) loops. (**b**) The TandemHeart centrifugal flow pump displaces oxygenated blood from the left atrium (*LA*) to a femoral artery, thereby reducing left ventricular preload. The net effect of immediate TandemHeart activation is a reduction in total LV volume and native left ventricular stroke volume (width of the PV loop). (**c**) Venoarterial extracorporeal membrane oxygenation (VA-ECMO) displaces venous blood from the right atrium (*RA*) through an extracorporeal centrifugal pump and oxygenator, then returns oxygenated blood into the femora artery. The immediate effect of VA-ECMO without a left ventricular decompression mechanism is an increase in left ventricular pressure and a reduction in left ventricular stroke volume

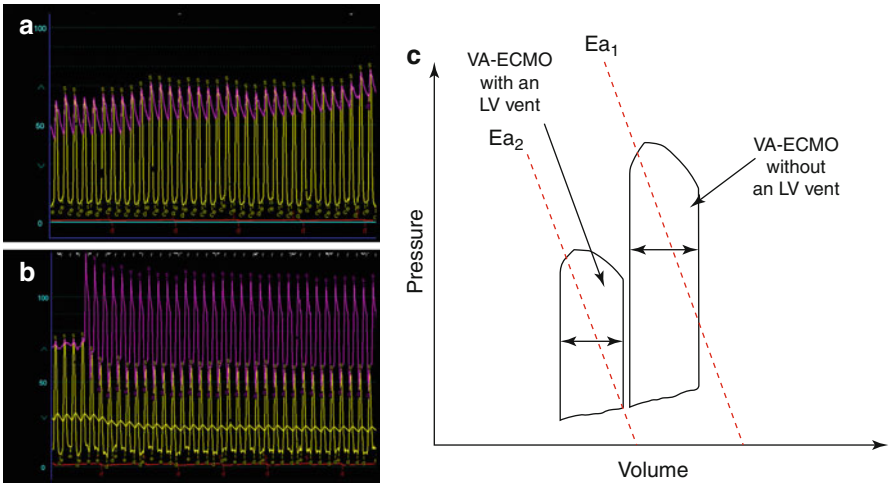

Fig. 36.6 Hemodynamic profile of veno-arterial extracorporeal membrane oxygenation (*VA-ECMO*) with and without left ventricular venting. (**a**) A double-lumen pigtail catheter during activation of VA-ECMO shows increased LV systolic pressure and reduced aortic pulse pressure. (**b**) Initiation of an IABP with VA-ECMO shows reduced LV systolic pressure (venting) and elevated aortic diastolic pressure. (**c**) Venting of the LV with either an IABP, Impella device or trans-septal left atrial cannula during VA-ECMO support, reduces LV end-systolic pressure and end-diastolic volume

veno-arterial extra-corporeal membrane oxygenation (VA-ECMO). VA-ECMO is more commonly used to enhance systemic oxygenation during cardio-respiratory collapse or biventricular failure. The major effect of VA-ECMO is to displace blood volume from the venous to the arterial circulation (Fig. 36.5) [6, 7]. As a result, a reduction in both right and left ventricular volumes can be observed with a concomitant increase in mean arterial pressure and both LV systolic and diastolic pressures. This increase in LV afterload or wall stress occurs in contrast to the Impella or TandemHeart devices since there is no direct venting of the left ventricle with VA-ECMO (Fig. 36.6). For this reason, operators have combined VA-ECMO with either an IABP, Impella device, or a trans-septal left atrial cannula to negate the effect of increased left ventricular afterload during VA-ECMO support [7, 8]. Advantages of VA-ECMO include the relative ease of insertion, the ability to support systemic oxygenation or biventricular failure, and the ability to provide cardiopulmonary support during ventricular tachycardia or fibrillation.

Indications

Clinical scenarios where these devices are commonly used include: cardiogenic shock, mechanical complications after AMI, high-risk coronary and non-coronary intervention, and for high-risk electrophysiologic ablations.

Contraindications

Major contraindications to Impella placement include the presence of a left ventricular thrombus, severe aortic valve insufficiency, and severe peripheral vascular disease. Major contraindications to TandemHeart placement include bleeding diathesis, severe peripheral vascular disease. Major contraindications for VA-ECMO include severe peripheral vascular disease, coagulopathy, and severe aortic valve insufficiency.

Equipment

The TandemHeart consists of a 21-Fr inlet cannula placed into the femoral vein and through the right atrium into the left atrium through a trans-septal puncture, an external impeller, and a 15-Fr outflow cannula placed into the femoral artery. The Impella consists of a catheter-mounted microaxial flow pump and a pigtail catheter that is inserted into the left ventricle, with the inlet and outlet areas on either side of the aortic valve. VA-ECMO employs a venous inflow cannula and an arterial outflow cannula. Both are attached to an extracorporeal centrifugal pump and oxygenator.

Technique

To deploy the Impella device, femoral artery access is first obtained and a guidewire is advanced into the apex of the left ventricle. The placement guidewire is then inserted into the lumen at the tip of the pigtail, until the catheter is successfully backloaded onto the guidewire. The catheter is then advanced under fluoroscopic guidance over the guidewire across the aortic valve using a fixed wire technique. The inlet area of the catheter should sit 3.5 cm below the level of the aortic valve. The guide is then removed, and proper placement is confirmed with fluoroscopy as well as using pressure waveforms from the Impella console. The TandemHeart requires a trans-septal puncture to deliver a left atrial inflow cannula and a separate arterial puncture for an outflow cannula. In contrast, percutaneous VA-ECMO requires a single venous puncture for delivery of a venous inflow cannula into the superior vena cava and an arterial puncture for an outflow cannula.

Complications

Potential complications of all pMCS devices include clinically significant hemolysis, device malfunction, major bleeding, aortic insufficiency, perforation, hematoma, arrhythmias, cerebrovascular accidents, cardiac tamponade, renal failure, or

vascular injury. Appropriate placement of the Impella device is crucial for proper functioning and to avoid the risk of device outflow obstruction. Echocardiography as well as the utilization of aortic and ventricular pressure waveforms from the device console should be used to guide placement. Similarly, the TandemHeart left atrial inflow cannula can displace into the right atrium and requires close monitoring with echocardiography. The major complication associated with VA-ECMO is left ventricular pressure overload, which requires close monitoring with a pulmonary artery catheter.

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