M-Mode Echocardiography

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Historically, M-mode (motion mode) was the first effective modality for the ultrasonic evaluation of the heart. M-mode echocardiography provides an ice pick, one-dimensional (depth only) view of the heart. The ultrasound echoes reflected from the various cardiac interfaces are represented as dots, and their intensities by brightness (B-mode). With the sweep of the screen (or the recording paper), the location of each interface is represented by a line, which provides information about its temporal location (Fig. 9.1). The two-dimensional (2D) appearance of the tracing is the result of presenting depth (expressed as the up-down dimension of the tracing) and width (left to right dimension, which expresses time).

An important attribute of M-mode echocardiography, compared with 2D imaging, is its superior temporal resolution. In the current 2D-directed M-mode, data is acquired at a rate up to 1000 frames per second, compared with 15 to 100 frames per second for 2D echocardiography, depending on sector width and heart rate. Thus M-mode echocardiography remains important in daily clinical use, for its ability to time events during the cardiac cycle and assess fast moving structures (e.g., valves) (see Fig. 9.1).

The limitations of M-mode are related to its one-dimensional nature. Although the interrogating ultrasound can be tilted to visualize different structures and their anatomic relations, it may miss other structures. Also, it may produce erroneous information about chamber and vessel dimensions by scanning them obliquely. Therefore M-mode tracings should always be obtained with the guidance of the two-dimensional images.

Some echocardiographers consider M-mode echocardiography to be a mere historical relic. Many of its initial uses during the earliest decade of echocardiography have been supplanted by the newer, more anatomically correct 2D, 3D, and Doppler modalities. We and others feel that like history itself, older experience is still worth studying. Moreover, in selected situations, M-mode remains a fundamental part of the routine echocardiographic exam and provides an important supplement to the newer echocardiographic modalities. Accordingly, this chapter will demonstrate classic M-mode images, with emphasis on its continued value in the era of 2D and 3D Doppler echocardiography.

LEFT VENTRICLE

The most common use for echocardiography, in any of its forms, is to assess size and function of the left ventricle (LV). At present, 2D-directed M-mode echocardiography is still used to establish cardiac chamber size and wall thickness (Fig. 9.2). Given its superior temporal resolution, M-mode echocardiography is perfectly suited to diagnosing abnormal LV contraction patterns, such as those seen with left bundle branch block (see Fig. 9.2, B).

It has long been appreciated that normal systolic function includes the descent of the mitral and tricuspid annulus toward the apex, which remains relatively stationary. The extent of the descent of the base, measured in millimeters, is reflective of global systolic function. Acronyms for this descent of the base are TAPSE (tricuspid annular plane systolic excursion) and MAPSE (mitral annular plane systolic excursion) (see Fig. 9.2, E).

MITRAL VALVE

Normal Motion

During the rapid ventricular filling in early diastole, the anterior mitral leaflet moves from its end-systolic closed position (D point) toward the opening position, that is, anteriorly toward the interventricular septum (E point); there is a reciprocal motion of the posterior leaflet (see Fig. 9.1, A, C). The nadir of this backward motion is called the F point. Atrial contraction reopens the leaflets (the A point.) Near the onset of systole, the leaflets move to the closed position (at the C point), where they remain throughout systole.

![Figure 9.1. Left ventricle. A, A schematic shows the four principal M-mode views of the heart. AMV, anterior mitral valve; ARV, anterior right ventricle; EKG, electrocardiograph; EN, endocardial edge; EP, epicardial surface; LA, left atrial; LS, left ventricular septum; LV, left ventricle; PLA, plasminogen activator; PLV, posterior left ventricle; PMV, posterior mitral valve; PPM, posterior papillary muscle; RS, right ventricular septum; RV, right ventricle.](image-url)
Figure 9.1—Cont’d B, M-mode of the mitral valve. C, M-mode transducer is directed through the RV, proximal aorta, and LA. AV aortic valve leaflets and AC aortic closure line, which, in normal individuals, is in the mid portion of the aorta. A, Anterior-most excursion of the anterior leaflet with atrial systole; C, closure of the mitral valve and end-diastole; D, posterior-most excursions of the mitral leaflets in early diastole; E, anterior-most excursions of the mitral leaflets in early diastole; F, closure point of the mitral valve in early diastasis; MV, mitral valve; RV, right ventricle. (A from Feigenbaum H. Echocardiography, Philadelphia: Lea & Febiger, 5th edition, 1993; adapted and used with permission.)

Figure 9.2. Left ventricle. A, Left ventricle of a patient with infiltrative cardiomyopathy due to amyloidosis. The walls are thick and the fractional shortening is low. B, Left bundle branch block. Compared to the normal LV echocardiogram (A), the initial downward motion of the septum (ESM) is absent, there is a prominent downward motion of the septum in early ventricular systole (the septal “beak” [SB]) which represents unopposed RV contraction, due to delayed activation of the posterior and lateral LV. Also, during ventricular systole, the septum moves anteriorly (arrow). Finally, there is a posterior septal motion (PSM), which occurs after the peak upward excursion of the posterior wall (LSM), and coincides with RV filling. C, Septal motion in severe TR. Notice the abrupt rightward motion (arrow) of the interventricular septum as the RV unloads into the RA during isovolumic systole. D, Example of normal tricuspid annular plane systolic excursion (TAPSE), defined as 16 mm or greater. LVIDd, diastolic LV dimensions; LVIDs, systolic LV dimensions.
Mitral Stenosis

The mitral leaflets open at early diastole. The leaflets are thickened with commissural fusion. The larger anterior leaflet moves anteriorly, which also pulls the smaller posterior leaflet anteriorly. Because of the pressure gradient across the valve throughout diastole and the lack of rapid ventricular filling phase, the leaflets do not return toward the closure position as in normal valves. The EF slope (see Fig. 9.1, B) is flatter than normal. The M-mode combination of leaflet thickening, anterior motion of the posterior mitral leaflet, and flat EF slope is diagnostic of mitral stenosis (Fig. 9.3, A).

Mitral Valve Prolapse

Unlike mitral stenosis, the valve diastolic motion is normal, and leaflets remain closed in systole. In mitral valve prolapse the closed mitral leaflets sag backward. This motion may occur in mid to late
Figure 9.3—Cont’d E, Early closure of the mitral valve in a patient with acute severe aortic regurgitation. Note that the mitral valve (arrow) closes well before the QRS complex, indicative of pressure equilibration between the LV and left atrium in this patient. F, Fine fluttering of the mitral valve at end diastole in a patient with aortic regurgitation. G, E point septal separation (arrow) in a patient with idiopathic dilated cardiomyopathy. LV, Left ventricle; MV, mitral valve; RV, right ventricle.

(Continued)
Figure 9.3—Cont’d H, Schematic diagram (left panel) and M-mode recording in a patient with elevated left ventricular diastolic pressure, showing the so-called B-bump (black arrow, right panel of schematic; blue arrow in patient M-mode). I, Color M-mode in a patient with complete heart block. Left arrow points to superimposed mitral regurgitation jet, which occurs in isovolumic systole. Right arrow points to diastolic mitral regurgitation seen in the left atrium, following nonconducted atrial depolarization. J, Use of M-mode echocardiography to estimate size of a proximal isovelocity systolic area (PISA). This adaptation of color M-mode allows for easy recognition of the extent of the PISA. A, Anterior-most excursion of the anterior leaflet with atrial systole; C, closure of the mitral valve and end-diastole; D, posterior-most excursions of the mitral leaflets in early diastole; E, anterior-most excursions of the mitral leaflets in early diastole; LA, left atrial pressure; LV, left ventricular pressure. (Schematic adapted and used with permission from Feigenbaum H. Echocardiography, ed 5. Philadelphia: Lea & Febiger, 1993.)
systole (see Fig. 9.3, B), and may be associated with mid-systolic click or pansystolic (and be associated with a pansystolic mitral regurgitation murmur). 7–9

Systolic Anterior Motion of the Anterior Mitral Leaflet

An anterior mitral leaflet that demonstrates systolic anterior motion (SAM) is seen mainly in patients with hypertrophic cardiomyopathy; high velocity in the left ventricular outflow tract results in systolic anterior motion of the anterior mitral leaflet, 10, 11 due to the Venturi effect. In these patients, the diastolic mitral valve motion is normal. During systole, however, the anterior leaflet moves toward the interventricular septum, and may coapt with the ventricular surface. The duration and degree of coaptation are related to the pressure gradient (see Fig. 9.3, C). 10, 11

The Mitral Valve in Aortic Insufficiency

In acute aortic regurgitation the diastolic pressure in the ventricle rises rapidly during diastole as a result of aortic runoff. In fact, in some instances the left ventricular pressure may rise above the LA pressure, leading to premature closure of the mitral valve (see Fig. 9.3, D, E). 9, 12, 13 When the aortic regurgitation jet strikes the anterior mitral leaflet, a fine, fluttering, motion can be seen. This finding suggests the presence of aortic insufficiency, but is not a marker of its severity (see Fig. 9.3, F). None of these findings in aortic regurgitation are reliably demonstrated by 2D echocardiography because of its inferior temporal resolution. Therefore M-mode data complements the assessment of valve regurgitation severity in contemporary practice.

The Mitral Valve in Left Ventricular Dysfunction

Normally the mitral E point is close to the interventricular septum (E point septal separation). In patients with left ventricular dilatation and reduced stroke volume, the E point of the anterior leaflet is separated from the septum by a distance of at least 8 mm. Interestingly, this expression of unfavorable LV remodeling was the first echocardiographic finding that appeared directly related to prognosis (see Fig. 9.3, G). 14–16 A second M-mode sign of LV dysfunction is a disturbance in the A-C line, which is usually rapid and straight. In patients with noncompliant LVs, atrial systole results in a significant elevation in LV diastolic pressures. The M-mode reflection of this phenomenon is an interruption in the normal A-C closure line, which is known as the A-C shoulder or B bump (see Fig. 9.3, H). 17, 18

Color M-Mode

This multiparametric display features flow events superimposed on the M-mode display and is perhaps the best method available to time regurgitant events. As is shown in Figure 9.3, I, color M-mode graphically demonstrates both systolic and diastolic mitral regurgitation in the same patient. Doppler color M-mode can be used for the measurement of the hemisphere maximum radius in the calculation of the proximal isovelocity area (PISA) 19 (see Fig. 9.3, J). This technique can be used when the MV leaflets are not well visualized, making it difficult to decide where to place the measurement of the PISA radius. We have also found this technique useful in cases of atrial fibrillation where the average of several PISA radii must be determined.

AORTIC VALVE

Normal Motion

The aortic valve can be seen in the middle of the aortic root. The right and the noncoronary cusps move in systole to the opened position, and they move in diastole toward the closed position, creating the impression of rectangles connected by strings (see Fig. 9.1, A, C). The ejection time, a descriptor of forward stroke volume, can be timed from the aortic valve opening to its closure. Fine fluttering of the opened leaflets is not uncommon. In patients with aortic stenosis, the leaflets appear thickened and calcified and have diminished excursion. A bicuspid aortic valve may have eccentric closure line (Fig. 9.4, A).
The Aortic Valve in Hypertrophic Obstructive Cardiomyopathy

In hypertrophic obstructive cardiomyopathy (HCM), the systolic anterior motion may result in left ventricular outflow tract obstruction, and therefore flow across the aortic valve will be decreased in midsystole. The M-mode will show a midsystolic closure of the aortic valve (see Fig. 9.4, B). In discrete subaortic stenosis to a subaortic membrane, by contrast, the valve opens well in early systole, and then suddenly returns to near closure position, where it stays for the rest of systole (see Fig. 9.4, C).

Premature Aortic Valve Opening

With severe aortic regurgitation, there is a rapid rise of left ventricular diastolic pressure and a rapid decline in the aortic diastolic pressure. With left atrial contraction, the left atrial (and left ventricular) diastolic pressure may rise above the aortic diastolic pressure, resulting in premature (end-diastolic) aortic valve opening (see Fig. 9.4, D).

PULMONIC VALVE

Normal Motion

In most cases where motion is normal, only the anterior leaflet of the pulmonic valve can be depicted on M-mode. This leaflet moves posteriorly and remains opened during systole. At end diastole, with right atrial contraction, the right ventricular pressure approaches the pulmonary arterial end-diastolic pressure, resulting in posterior motion of the pulmonic valve (A-wave) (Fig. 9.5, A).\(^2,20,21\)

Severe Pulmonary Hypertension

In severe pulmonary hypertension, the pulmonary artery diastolic pressure is much higher than the right ventricular diastolic pressure. In this hypertension situation, the right atrial contraction will have no effect on the pulmonic valve end-diastolic position. No A-wave is seen, in spite of normal sinus rhythm (see Fig. 9.5, B). Another finding seen in pulmonary hypertension is the “flying W” sign seen during pulmonic valve systolic opening. This unusual motion, with...
midsystolic closure and late systolic opening, may be the result of increased pulmonary vascular resistance. The abnormal absence of the pulmonic valve A-wave, together with the presence of flying W sign, are highly suggestive of severe pulmonary hypertension. They can be used when Doppler estimation of pulmonary artery pressure is not possible because of the lack of tricuspid or pulmonic regurgitation.

PERICARDIAL DISEASE

Pericardial effusion is better demonstrated by 2D echocardiography than by M-mode echocardiography. However, the timing of the abnormalities seen in cardiac tamponade and constrictive pericarditis can contribute to the understanding of the pathophysiology of these conditions; this issue is reviewed in Figure 9.6.

CARDIAC TAMPONADE

M-mode can demonstrate pericardial effusion as well as the respiratory variations in ventricular size and valve excursion. Because of ventricular interdependence, inspiration results in less pulmonary venous return and transmural flow, which leads to a phasic decline in left ventricular volume. This process is reversed during inspiration. The M-mode echocardiogram (recorded simultaneously with respiratory tracing) shows the septal inspiratory shift toward the LV. This is the echocardiographic equivalent of the paradoxical pulse.

The exact timing of diastolic right ventricular collapse can also be demonstrated by M-mode echocardiography (see Fig. 9.6, A, B). In some cases of pulmonary hypertension or chronic right-sided pressure overload with RV hypertrophy, LA or even LV collapse may occur before RV or RA collapse is seen. This may also be seen in instances of low filling pressure. The elevation of right atrial pressure seen in most cases of tamponade can be confirmed by M-mode tracing of the inferior vena cava (IVC) near its communication with the right atrium. An IVC diameter of more than 20 mm, with reduced (less than 50%) decrease during inspiration or “sniff” indicates elevated right atrial pressure, usually greater than 15 mm Hg (IVC plethora) (see Fig. 9.6, C).

CONSTRUCTIVE PERICARDITIS

This difficult clinical diagnosis can still be supported by an array of M-mode echocardiographic findings. These findings include (1) pericardial thickening; (2) IVC plethora (see earlier discussion); (3) inspiratory septal shift toward the LV (The right ventricular...
cavity dimension increases during inspiration and decreases during expiration, and there are reciprocal changes in the LV. During expiration, the mitral valve opening duration is longer than that during inspiration (see Fig. 9.6, D); (4) diastolic septal “bounce” (characteristic early diastolic notch) as well as a late diastolic reverberation in the septum, around the time of atrial contraction (see Fig. 9.6, D, E); and (5) premature opening of the pulmonic valve due to elevation of the right ventricular end-diastolic pressure without pulmonary hypertension, and relatively low pulmonary artery diastolic pressure.

Figure 9.6. Pericardial disease. A, Cardiac tamponade: Large pericardial effusion and diastolic collapse of the right ventricular free wall, indicated by the arrow. B, Large circumferential pericardial effusion (upper pair of downward arrows) and left atrial collapse (lower pair of downward arrows), indicating increased intrapericardial pressure leading to ventricular diastolic and left atrial systolic collapse. When filling pressures are low, this constellation of findings is called low pressure cardiac tamponade. C, In patient with tamponade, the vena cava is dilated and does not collapse. D, Constrictive pericarditis. E, Schematic of normal septal motion (left) and recording from a patient with constrictive pericarditis. Note the diastolic posterior motion of the septum (DM), as well as the second reverberation in the septum (ASM), which corresponds to atrial systole.
Four modalities of Doppler echocardiography are currently available for use with a wide variety of applications: pulsed wave (PW) Doppler, continuous wave (CW) Doppler, color flow imaging, and tissue Doppler imaging. Each modality plays an important role in the overall assessment of the patient with heart disease. Whereas M-mode and two-dimensional echocardiography provide structural and functional data, tissue Doppler imaging supplements the assessment of myocardial function, including diastolic function. Doppler echocardiography is the modality on which noninvasive assessment of cardiac hemodynamics depends. The purpose of this chapter is to review the normal antegrade intracardiac flow using PW and CW.

**BASIC CONCEPTS**

Doppler echocardiography is based on the important concept that backscattering of the ultrasound from moving blood cells will appear higher or lower in frequency than the transmitted frequency depending on the speed and direction of blood flow. Velocities are calculated using the formula:

\[
\Delta F = \frac{V \times 2Fo \times \cos \theta}{C}
\]

where \(\Delta F\) represents Doppler shift (the difference between the transmitted frequency and the backscattered frequency), \(V\) is the velocity of the moving blood cells, \(Fo\) is the transducer frequency, \(\cos \theta\) is the cosine of the angle of the incidence, and \(C\) is the velocity of propagation in the soft tissues, including the myocardium. For cardiac applications, the velocity of propagation in the myocardium is 1540 M/sec and \(\cos \theta = 1\) (because the angle of the incidence is 0 or 180 degrees). To calculate Doppler velocities, the formula can be rearranged:

\[
V = \frac{\Delta F \times C}{2Fo \times \cos \theta}
\]

All commercially available ultrasound machines provide flow velocity data. Quantification of flow velocity is obtained with either PW or CW Doppler. PW Doppler records flow velocities at one specific location, whereas CW Doppler records flow velocity along the entire pathway of the ultrasound beam (Fig. 10.1). The former is used to quantitate flow in a given lumen, but can only measure velocity over a limited range. The latter permits the measurement of high velocity flows, but does not determine the location of the signal because signals from the entire length of the ultrasound beam are included in the spectral CW Doppler tracing. By convention, flow toward the transducer is displayed, spectrally, above the zero baseline and flow away, below the zero baseline. By convention in echocardiography, the y-axis is the velocity (in m/sec) and the x-axis represents time (in seconds). PW Doppler is used to assess velocities across normal valves or vessels to calculate flow and assess cardiac function. Common applications include measurements of stroke volume (SV), cardiac