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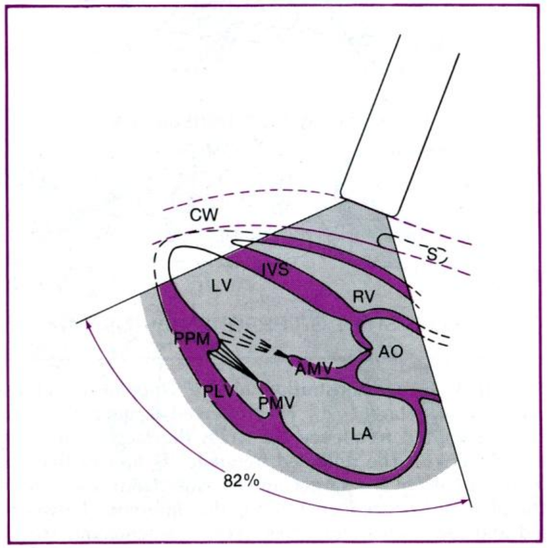
ВЫСШЕГО ПРОФЕССИОНАЛЬНОГО ОБРАЗОВАНИЯ
«КАЗАНСКИЙ ГОСУДАРСТВЕННЫЙ МЕДИЦИНСКИЙ УНИВЕРСИТЕТ
ФЕДЕРАЛЬНОГО АГЕНСТВА ПО ЗДРАВООХРАНЕНИЮ
И СОЦИАЛЬНОМУ РАЗВИТИЮ»
КАФЕДРА ПРОПЕДЕВТИКИ ВНУТРЕННИХ БОЛЕЗНЕЙ

Введение в клиническую эхокардиографию

Учебно-методическое пособие

Introduction to Clinical Echocardiography

Manual



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Авторы-составители:
заведующий кафедры пропедевтики внутренних болезней, профессор В.Н.Ослопов, доцент А.Р.Садыкова.

Рецензенты:
декан отделения по работе с иностранными студентами,
к.м.н., доцент кафедры эпидемиологии
Н.М.Хакимов

методист УМУ КГМУ,
к.м.н., доцент кафедры пропедевтики внутренних болезней
О.В.Богоявленская

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Учебно-методическое пособие составлено в соответствии с Государственным образовательным стандартом высшего профессионального образования (2000), Государственными требованиями к минимуму содержания и уровню подготовки выпускника вуза по специальности 040100 «Лечебное дело», типовой и рабочей программами по дисциплине «Пропедевтика внутренних болезней» (2003). В учебно-методическом пособии подробно освещается содержание занятий, даны теоретические и справочные материалы, описываются практические умения в четкой последовательности диагностических действий. Пособие предназначено для иностранных студентов медицинских вузов.

PRINCIPLES OF ECHOCARDIOGRAPHY
CREATION OF IMAGES USING PULSED REFLECTED ULTRASOUND

The term echocardiography refers to a group of tests that utilize ultrasound to examine the heart and record information in the form of echoes, i.e., reflected sonic waves. The upper limit for audible sound is 20,000 cycles/second, or 20 kiloHertz (kHz — 1000 cycles/second). The sonic frequency used for echocardiography ranges from 1 to 10 million cycles/second, or I to 10 megaHertz (MHz). In adults the frequencies commonly employed are 2.0 to 5.0 MHz, while in children they are usually higher, ranging from 3.5 to 10.0 MHz. The resolution of the recording, which is the ability to distinguish two objects that are spatially close together, varies directly with the frequency and inversely with the wavelength. High-frequency (short wavelength) ultrasound can identify separate objects that are less than 1 mm apart. Beams having lower frequencies and longer wavelengths have poorer resolution. However, the degree of penetration, which is the ability to transmit sufficient ultrasonic energy into the chest to provide a satisfactory recording, is inversely proportional to the frequency of the signal. Since a high-frequency ultrasonic beam (i.e., 5 or 10 MHZ) is unable to penetrate a thick chest wall, lower frequency ultrasonic beams are used in adults. While this permits penetration through the chest wall, it partially sacrifices resolution; however, even with a transducer producing a beam of 2.50 MHz, which is commonly used in adult echocardiography, it is possible to resolve objects that are 1 to 2 mm apart.

Principles of Ultrasonic Imaging

The principles by which ultrasound creates an image are depicted in Figure 1. The transducer at the side of the beaker of water has a piezoelectric element that vibrates very rapidly and produces ultrasound when activated by an electrical field. If a burst of electrical energy is imparted to the transducer, it will emit a burst of ultrasound, which travels through the beaker. As long as the medium through which the sound travels is homogeneous, the ultrasonic waves will travel in a straight line. When the ultrasound strikes an interface between two media that have different acoustical properties, the sound behaves according to the laws of reflection and refraction, analogous to light. Whether or not ultrasound is reflected by an interface depends upon the difference in the acoustical impedances of the two media. Although acoustical impedance is the product of the density of the object and the velocity of sound through that object, for all practical purposes one can consider the acoustical impedance to be a function of density. Thus, if the interface is between a liquid and a solid, the ultrasonic wave will generally be reflected. If the interface is between two solids of different densities, the quantity of reflected ultrasound is usually less. Thus the quantity of energy reflected is directly proportional to the difference in the acoustical impedances (or densities) of the object and its surrounding media.

The left panel of Fig. 1 shows diagrammatically an ultrasonic beam, which consists of individual bursts of ultrasound that leave the transducer, travel through the fluid, strike the far side of the beaker, are reflected by this interface, retrace their original path, and again strike the transducer. The piezoelectric element in the transducer not only converts electrical energy into ultrasonic impulses but also converts ultrasound back, to electrical energy. Thus, when the reflected ultrasound (echo) strikes the piezoelectric element in the transducer, an electrical signal is produced. If the time it takes for (1) the ultrasound to leave the transducer and return and (2) the velocity of sound through the medium are both known, the distance between the transducer and the reflected interface can be calculated.

By calibration of the echograph for a velocity of sound in the medium under examination the time that it takes for the ultrasound to leave and return as an echo can be automatically converted to distance. Thus, the far wall of the beaker is depicted on the oscilloscope as being 6 cm from the transducer.

If a rod is placed in the water so that it transects the ultrasonic beam, part of the energy will strike it and be reflected by the rod before the beam strikes the far side of the beaker. Thus, the returning ultrasonic energy or echo from the rod will strike the transducer sooner than that returning from the far side of the beaker, and the corresponding electrical signal produced by the echo from the rod will be closer to the transducer than will that from the beaker. Also, since some of the ultrasonic energy is reflected by the rod, less energy will remain to strike the far wall of the beaker, and the magnitude of the echo (Fig. 1, center panel) will be

reduced. If the interface is a very strong reflector of sound, no energy may transverse the object and no images are obtained behind the object, i.e., acoustic shadowing.

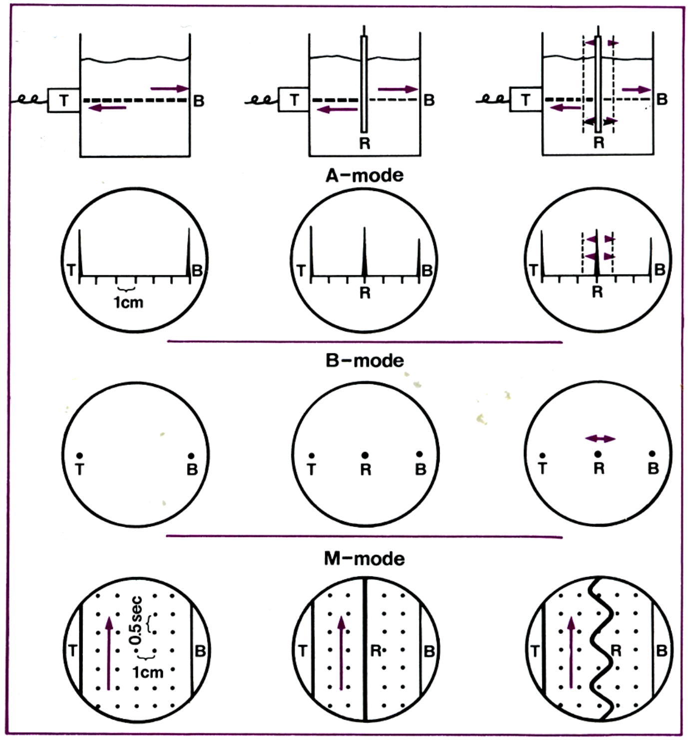

Fig. 1 The principles of acoustic imaging using pulsed reflected ultrasound (see text for details). T = transducer; B — beaker; R — rod. (Modified from Feigenbaum, H., and Zaky, A.: Use of diagnostic ultrasound in clinical cardiology. J. Indiana State Med. Assoc.59:140, 1966.)

There are adjustments in ultrasonic instrumentation that provide depth compensation and thereby correct for the usually gradual loss of ultrasonic energy from distant or far objects. From examination of the A-mode echo (“A” refers to amplitude) in Fig. 1 (center panel), one could deduce that the far wall of the beaker is 6 cm from the transducer and that an echo-reflecting object is present in the center of the beaker, 3 cm from the transducer.

Imaging a Moving Object

If the rod were moving back and forth as in the right panel of Figure 1, the ultrasonic examination would differ. The transducer functions as a transmitter of ultrasound for a very short time, just over I μsec in commercial echocardiographs. During the remaining time the transducer functions as a receiver, waiting for echoes to be converted into electrical signals. The rapidity of the repetition rate with which the transducer fires the 1 μsec impulses varies depending upon the design of the instrument, in most situations the transducer functions as a receiver for over 90 per cent of the time.

A-Mode, B-Mode, and M-Mode Presentations

In the left and center panels of Fig.1, the wall of the beaker and the rod are not moving. All the ultrasonic impulses firing at a rate of 1000/sec take the same time to leave the transducer and return as echoes. Therefore the signals or echoes seen on the oscilloscope are static. In the right panel, the object moves constantly, the time required for the ultrasound to leave the transducer and return as an echo varies correspondingly, and the echo signal on the oscilloscope moves. In the A-mode presentation the echo from the rod moves back and forth within the center of the beaker. To record the motion of the rod, one converts the amplitude of the echo to brightness, which changes the display from the A-mode to the B-mode ("B" refers to brightness), in which the returning echoes are displayed on the oscilloscope as dots rather than as spikes. Stronger signals are therefore taller on the A-mode and brighter on the B-mode presentation. On the M-mode presentation ("M" refers to motion), displayed in Fig.1, the oscilloscope sweeps from bottom to top. in the left and center panels the structures are fixed, and therefore the M-mode presentation shows simply a series of parallel lines. In the right panel the rod moves back and forth regularly, its echo inscribing a sinusoidal curve on the M-mode oscilloscope.

Thus, the M-mode presentation permits recording of amplitude and of the rate of motion of moving objects with great accuracy; the sampling rate is essentially 1000 pulses/sec, the repetition rate of the transducer. Because electrocardiograms and other cardiac parameters are conventionally displayed on the oscilloscope together with the echocardiographs, the oscilloscope usually sweeps from left to right rather than from bottom to top; therefore the transducer is generally

displayed at the top of the oscilloscopic image rather than on the left side, as depicted in Fig.1.

M-Mode Echocardiography

TECHNIQUE. The ultrasonic transducer is ordinarily placed on the surface of the chest, usually along the left sternal border, and the ultrasonic beam is directed toward the part of the heart lobe examined, In Figure 2 the ultrasound is depicted as passing through a small portion of the right ventricle, the interventricular septum, and the cavity and posterior wall of the left ventricle, Structures such as the chest wall that do not move with cardiac activity are depicted as horizontal lines. Cardiac walls and valves that move with cardiac action inscribe wavy signals, while the blood-filled cavities are relatively echo free.

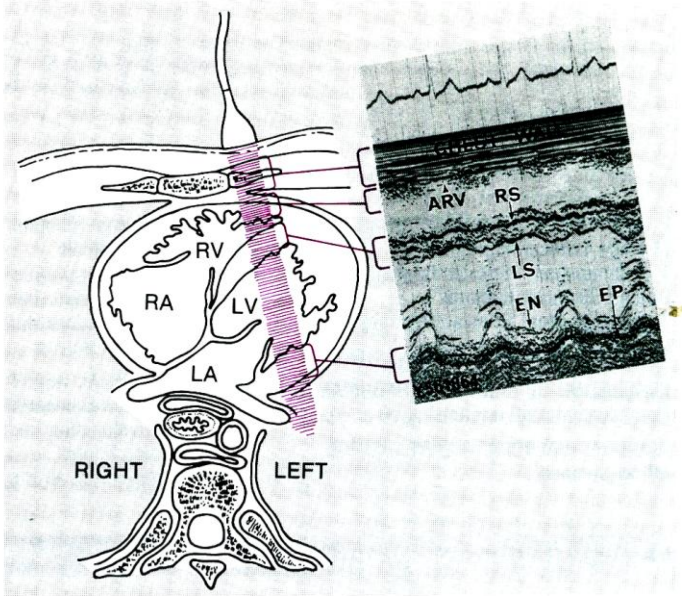

Fig.2. Cross-section of the heart and corresponding echocardiogram showing the cardiac structures transected by an ultrasonic beam directed toward the left ventricle. The ultrasound passes through the chest wall, the anterior right ventricular wall (ARV), a small portion of the right ventricular cavity, the interventricular septum, the cavity of the left ventricle, and the posterior left ventricular wall. RS = right side of the interventricular septum; LS = left side of interventricular septum; EN = posterior left ventricular endocardium; EP = posterior left ventricular epicardium.

THE M-MODE TRACING. An M-mode recording is sometimes called a one-dimensional or an "ice pick" view of the heart. However, since time is the second dimension on M-mode tracings, this display is not truly one-dimensional. The information provided by an isolated M-mode view of the heart, as in Fig.2, can be augmented by changing the direction of the ultrasonic beam, as in an arc or sector. With the transducer placed along the left sternal border in approximately the third or fourth intercostal space, the ultrasonic beam can be swept in a sector between the apex and the base of the heart. When the transducer is pointed toward the apex of the heart. the ultrasonic beam traverses the left ventricular cavity at the level of the papillary muscles and passes through a small portion of the right ventricular cavity (Fig. 3, position 1).

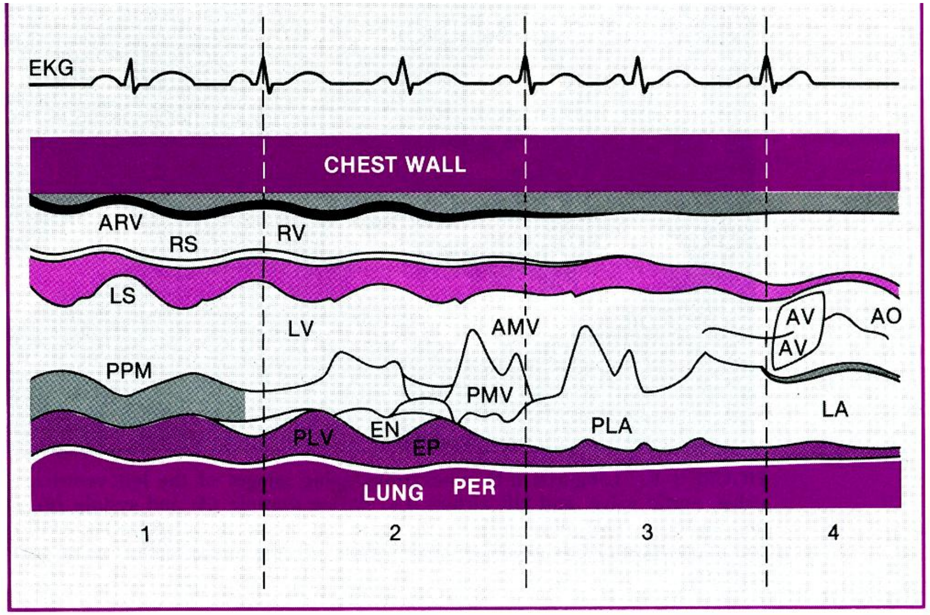

Fig. 3. Presentation of an M-mode echocardiogram as the transducer is directed from the apex (position 1) to the base of the heart (position 4). Areas between the dotted lines correspond to the transducer position. EN = endocardium of the left ventricle; ISP = epicardium of the left ventricle; PER = pericardium; PLA = posterior left atrial wall.

Tilting the transducer superiorly and.medially causes the ultrasonic beam to traverse the left ventricular cavity at the level of the edges of the mitral valve leaflets or the chordae (position 2). The beam again passes through a small portion of the right ventricle. By directing the transducer more superiorly and medially (position 3), more of the anterior leaflet of the mitral valve can be recorded and the beam may traverse part of the left atrial cavity. Further tilting of the transducer superiorly and medially (position 4) directs the beam through the root of the aorta, the leaflets of the aortic valve, and the body of the left atrium.

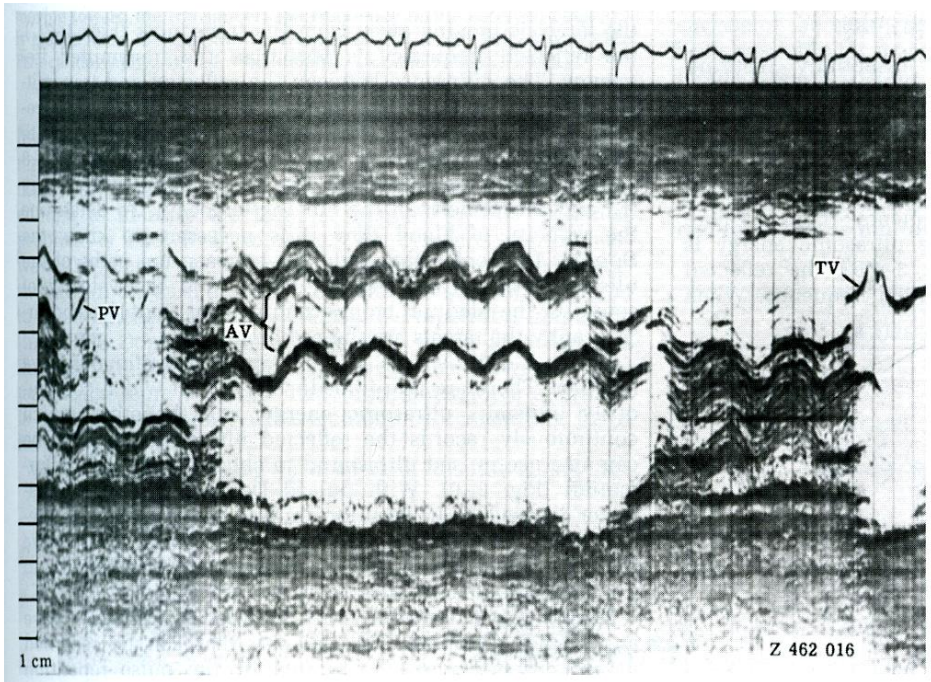

Fig.4. M-mode scan recording echoes from a pulmonic valve (PV), aortic valve (AV), and tricuspid valve (TV).

Figure 4 shows echoes from the aorta and aortic valve; by tilting the transducer medially from the aortic valve, it is possible to record the anterior leaflet of the tricuspid valve, which is similar in appearance to the recording from the anterior leaflet of the mitral valve. When the transducer is directed superiorly and laterally from the aortic valve, a posterior leaflet of the pulmonary valve can be recorded (Fig.4).

Two-Dimensional Echocardiography

The principle of two-dimensional (2-D) echocardiography is depicted in Figure 5.

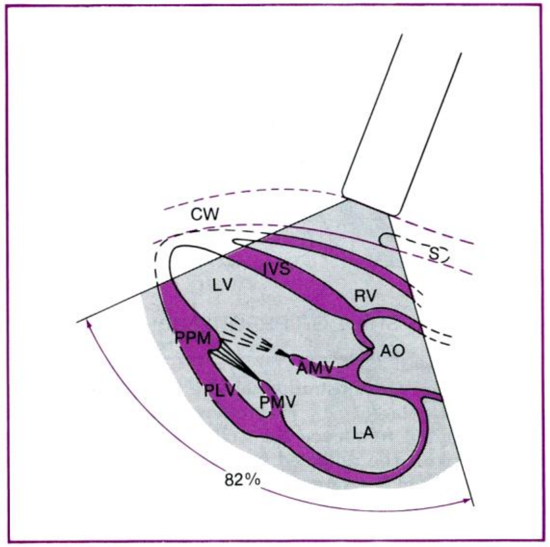

Fig.5. How to obtain a cross-sectional or 2-D image of the heart parallel to the long axis of the left ventricle. CW = chest wall.

The ultrasonic beam now moves in a sector so that a pie-shaped slice of the heart is interrogated. Most commercial 2-D echocardiographs move the ultrasonic beam so that approximately 30 slices/sec are obtained. The ultrasonic beam can be moved mechanically by oscillating a single transducer or by rotating a series of transducers. The ultrasound can also be steered electronically using the so-called phased array principles, in which multiple ultrasonic elements are utilized to make up the beam and in which the firing sequence of the elements is controlled. A computer or microprocessor is necessary to control the firing of the elements and the direction of the beam. Figure 6 illustrates two individual frames representing stop-action sequences from a videotape

recording of a normal heart in which the mitral and aortic valves and parts of the left ventricle, left atrium, and right ventricle are imaged.

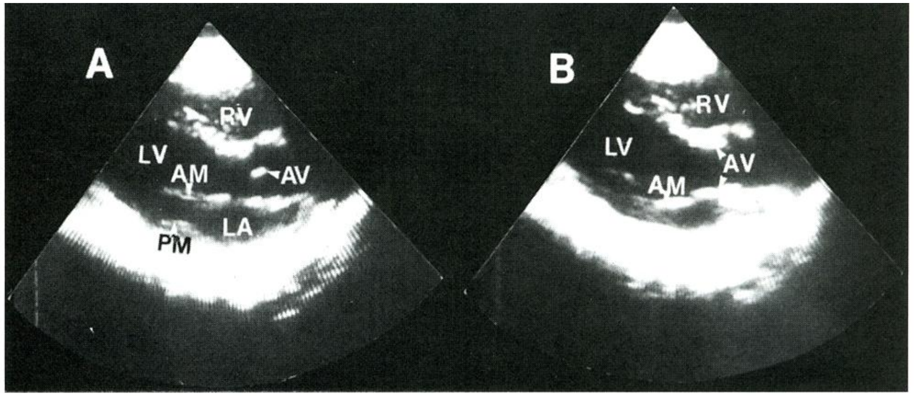

Fig. 6. Long-axis 2-D echocardiographic images of the left ventricle (LV), right ventricle (RV), mitral valve, aortic valve, and left atrium (LA) during diastole (A) and systole (B). During diastole the anterior (AM) and posterior (PM) mitral leaflets are apart and the aortic valve leaflets (AV) come together as a single echo in the midportion of the aorta (A). With systole (B), the mitral leaflets come together and the aortic valve leaflets separate.

Doppler Echocardiography

M-mode and 2-D echocardiography essentially create ultrasonic images of the heart. Doppler echocardiography utilizes ultrasound to record blood flow within the cardiovascular system. The principle of the Doppler effect is illustrated in Figure 7. If the ultrasonic beam is reflected by a stationary object (Fig. 7A), the transmitted frequency (f_t) and the reflected frequency (f_r) are equal. However, if the target reflecting the ultrasonic energy is moving toward the transducer (Fig. 7B), the reflected frequency is greater than the transmitted frequency. When the target is moving away from the transducer (Fig. 7C), the reflected frequency is less than the transmitted frequency. The difference between the reflected and transmitted frequencies represents the Doppler shift or Doppler frequency. By knowing the Doppler frequency it is possible to calculate the velocity of the moving target. Figure 8 shows the Doppler equations that relate Doppler frequency (f_d) and the velocity of the moving target (v). To determine the velocity of blood flow it is necessary to know the Doppler frequency, the angle (Θ) between the paths of the ultrasonic beam and moving target, and the velocity of sound in the medium being examined; in Doppler echocardiography the targets are the red blood cells.

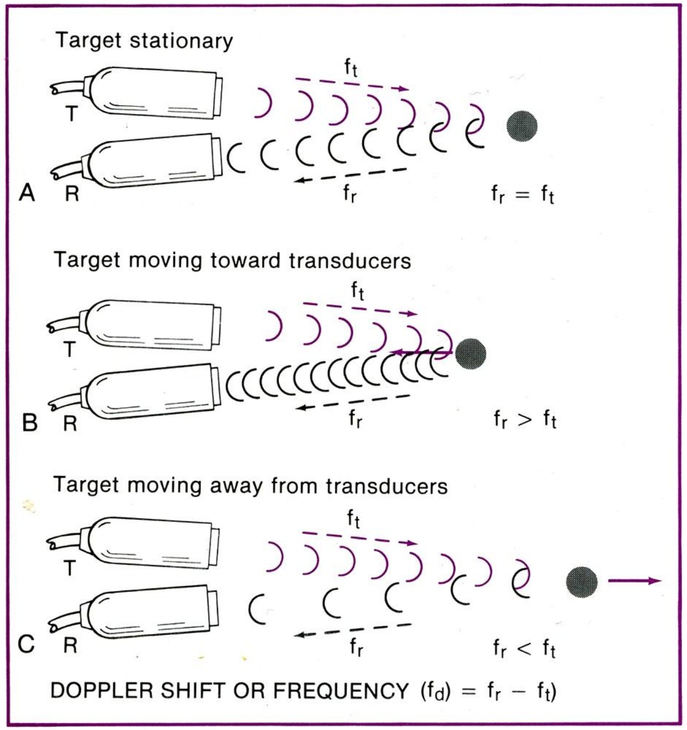

Fig.7. Demonstration of the Doppler effect using reflected sound from a target (A). The reflected frequency (f,) is greater than the transmitted frequency (f1) when the target is moving toward the transducer (B). The reflected frequency is smaller than the transmitted frequency when the target moves away from the transducer (C). The Doppler shift or frequency (fd) is the difference between the transmitted and reflected frequencies.

Figure 7 illustrates the principles of continuous-wave Doppler. There are two transducers, one of which continilously transmits ultrasonic energy, and the other, which continuously records the reflected ultrasonic signals. One can also use pulsed ultrasound to obtain the

Doppler information (Fig. 9). With pulsed Doppler only one transducer is needed. In addition, pulsed Doppler permits creation of a simultaneous M-mode or 2-D image. To derive the Doppler frequency, the frequencies of the reflected and transmitted bursts of ultrasound are subtracted.

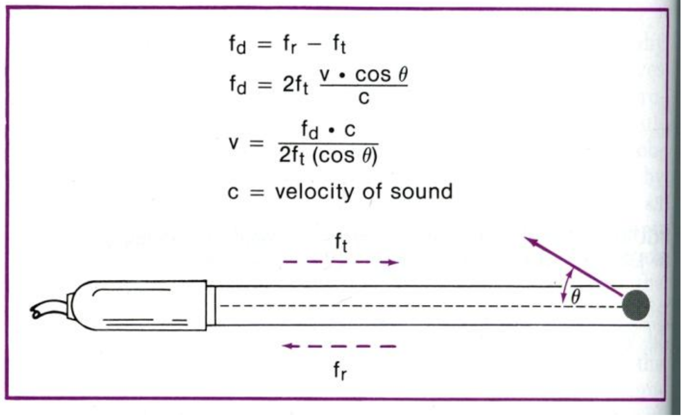

Fig.8. Doppler equations relating Doppler frequencies (id), received frequency (sr), transmitted frequency (fr), and the angle (0) between the direction of the moving target and the path of the ultra sonic beam.

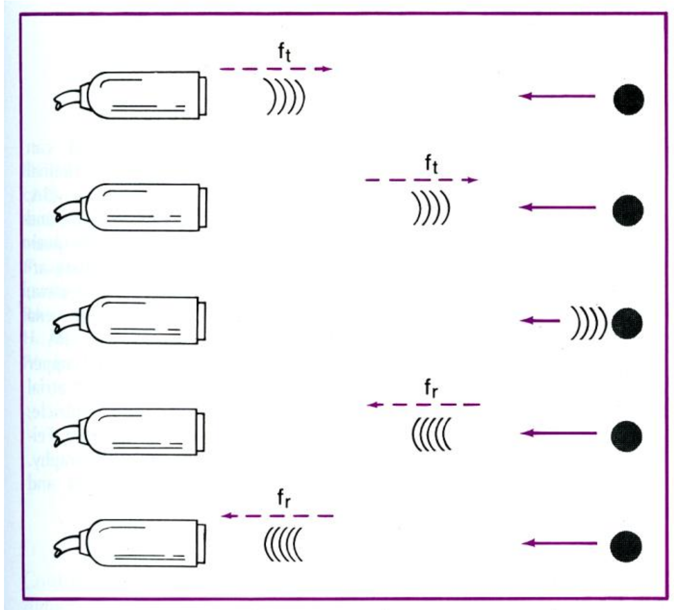

Fig.9. Demonstration of the principle of pulsed Doppler echocardiography. If the object reflecting the pulses with ultrasound is moving toward the transducer, the frequency of the received pulse (f_r) is greater than the transmitted frequency (f_t).

Significant differences exist between continuous wave and pulsed Doppler. The velocity that can be recorded using pulsed Doppler is limited by the pulse repetition frequency of the system. Thus, if the blood is moving very rapidly, as might occur when it is passing through a stenotic valve, then pulsed Doppler cannot sample rapidly enough to identify the Doppler frequency. This technical problem is known as aliasing. As a result, continuous- wave Doppler is necessary for recording very high velocities within the cardiovascular system. An alternative way is to use a multiple pulsed or high pulse repetition frequency (high PRF) Doppler system. High PRF allows simultaneous imaging and recording of high flow rates; however, it is technically more difficult. The continuous wave approach is the more commonly used technique for recording high- frequency flows.

The Doppler recording is a spectral display using fast Fourier analysis of the audible Doppler signal. The recording is usually on strip chart paper or videotape and is commonly referred to as spectral Doppler. The audio signal is helpful in interpreting the various types of flow and represents an important aspect of the Doppler examination.

Color Doppler

Doppler information from the cardiovascular system can also be recorded in a spatially correct format superimposed on an M-mode or 2-D echocardiogram. Doppler flow imaging is created by multiple Doppler gates that are spatially correct and display the moving blood within the 2-D or M-mode recording. The direction of the blood is displayed in color. With this particular instrument blood moving toward the transducer is depicted in shades of yellow and red, whereas blood moving away from the transducer is in shades of blue. The tracing shows how turbulent flow can be displayed as green or as a mosaic of colors.

Advantages and limitations of EchoCG.

The advantages of echocardiography are numerous. The examination is painless, as best as can be determined it is virtually harmless, and it is less costly than other sophisticated imaging techniques. However, some technical difficulties exist that require expertise on the part of the examiner and interpreter of the echocardiographic recordings. The principal problem is posed by the poor transmission of ultrasound through bony structures or air-containing lungs. The examiner must thus try to avoid these structures. A variety of techniques have been developed to circumvent this problem. The patient is commonly placed in the left recumbent position to move the heart from beneath the sternum. The subxiphoid or subcostal transducer position is frequently used in patients with hyperinfiated lungs and a low diaphragm. Transesophageal echocardiography is available for the patient in whom the examination is extremely difficult. Thus, many examining techniques have been developed to minimize the technical difficulties in performing an echocardiographic examination.

Examination of the normal heart

TWO-DIMENSIONAL ECHOCARDIOGRAPHY. An infinite number of slices of the heart can theoretically be obtained using 2-D echocardiography. The American Society of Echocardiography has attempted to standardize and simplify the many 2-D examinations. The Society thought that all views could be categorized into three orthogonal planes, as illustrated in Figure 10. These planes are the long-axis, short-axis, and four-chamber. The long-axis plane is the imaging plane that transects the heart perpendicular to the dorsal and ventral surfaces of the body and parallel to the long axis of the heart. The plane transecting the heart perpendicular to the dorsal and ventral surfaces of the body, but perpendicular to the long axis of the heart, is defined as the short-axis plane. The plane that transects the heart approximately parallel to the dorsal and ventral surfaces of the body is referred to as the four-chamber plan. It should be emphasized that these views or planes are with reference to the heart and not the thorax or body.

<u>Transducer Locations.</u> These ultrasonic planes or views can be obtained from more than one transducer location. Figure 11A demonstrates that the long-axis view can be obtained with the transducer

in the apical position, in the parasternal position (left sternal border), or in the suprasternal notch.

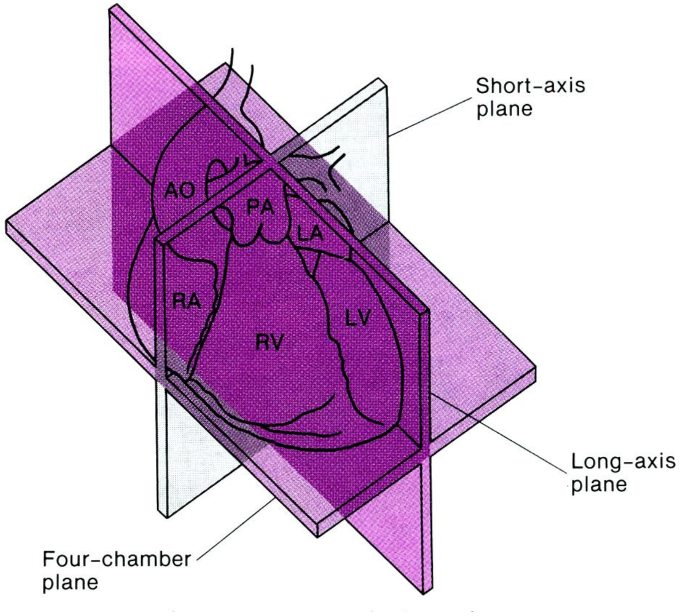

Fig.10. The three orthogonal planes for 2-D echocardiographic imaging. AO = aorta; PA = pulmonary artery; LA — left atrium; RA = right atrium; RV = right ventricle; LV = left ventricle.

A short-axis view (11B) cuts across the heart so that the left ventricle resembles a circle. The right ventricle can be seen curving around the left ventricle. Such an examination can be obtained with the transducer in the parasternal position or in the subcostal (subxiphoid) position. The four-chamber view is depicted in Figure 11C. Such a view permits the examination of all four cardiac chambers simultaneously. This type of examination can be obtained with the transducer over the cardiac apex or with the transducer in the subcostal position.

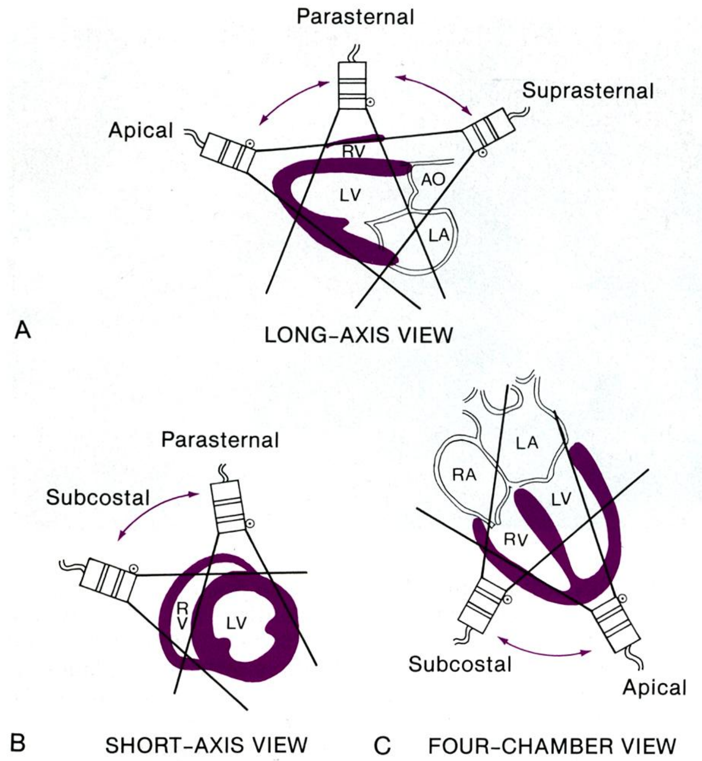

Fig.11. How the various orthogonal planes can be obtained from different transducer positions.

Figure 12 diagrammatically illustrates two commonly used 2-D echocardiographic views with the transducer placed at the cardiac apex. Plane 1 demonstrates an apical four-chamber view of the heart and plane 2 is a longitudinal slice through the left ventricle and atrium, the so-called two-chamber view. The two-chamber view does not exactly fit the three-plane scheme, since it is between the four-chamber and long-axis planes.

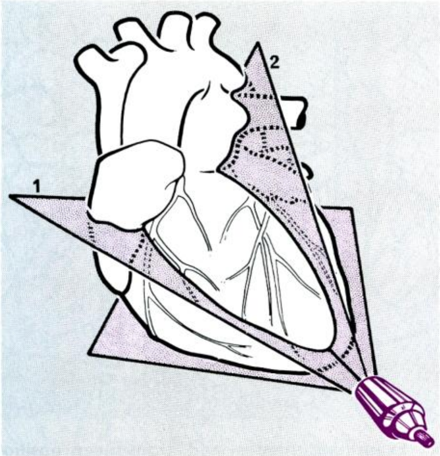

Fig.12. Transducer position and examining planes for apical 2-0 echocardiograms. Plane 1 passes through the four-chamber plane of the heart. Plane 2 represents the path of the ultrasonic beam for the two-chamber apical examination.

The subcostal transducer location produces examinations roughly in the four-chamber and short-axis planes. The ultrasonic plane indicated in Figure 13A is similar to examining plane 1 in Figure 12.

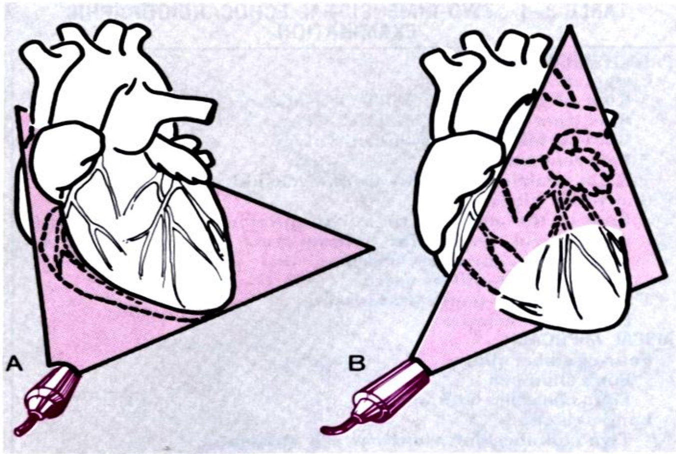

Fig. 13. Transducer position and examining planes for a subcostal four-chamber examination (A) and a subcostal short-axis examination (B).

The resulting subcostal four-chamber echocardiogram appears in Figure 13A. Figure 13B shows how the transducer can be rotated 90 degrees to provide a subcostal short-axis examination of the heart. The subcostal four-chamber view is particularly helpful in examining the interatrial and inter- ventricular septa. By directing the transducer in a slightly modified short-axis examination, one can obtain an excellent view of the right side of the heart. The subcostal location also permits an opportunity to direct the ultrasonic beam through the inferior vena cava and hepatic veins.

The two examining planes with the transducer in the suprasternal notch are depicted in Figure 14.

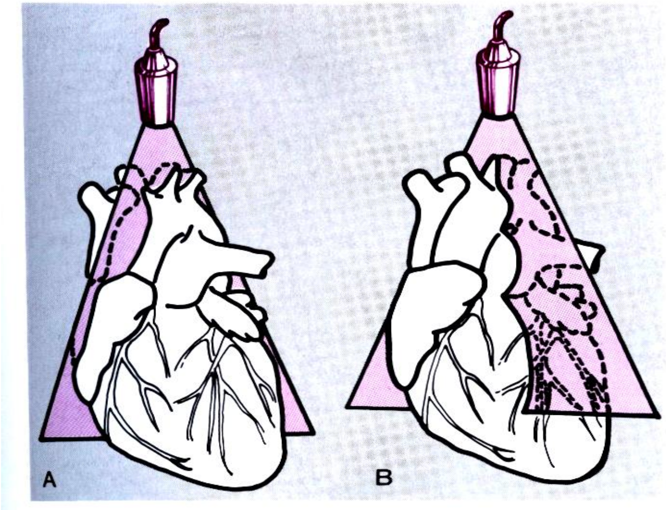

Fig.14. Transducer position in examining planes for the suprasternal examination parallel to the arch of the aorta (A) and perpendicular to the arch of the aorta (B).

It is probably best to orient the ultrasonic beam with regard to the arch of the aorta rather than to the heart, since one does not record much of the heart with the transducer in this position, especially in the adult. In addition, the planes are different from those with the transducer at the apex or subcostal region. Thus, better terminology with regard to the examining plane from the suprasternal localion would be parallel or perpendicular to the arch of the aorta.

M-MODE ECHOCARDIOGRAPHY. With the advent of 2-D echocardiography, and to some extent Doppler echocardiography, the M-mode examination now plays a lesser role in the ultrasonic examination of the heart The principal advantage of this examination is the high temporal resolution inherent in sampling cardiac motion at roughly 1000 times/second. One can utilize this examination to demonstrate subtle motion of cardiac structures. Figure 3—30 is an M-mode study of a normal mitral valve. One can appreciate the motion of the anterior and posterior leaflets with far greater detail than can be seen with a 2-D study that usually samples at 30 frames/sec. For example, the mid-diastolic reopening of the valve, which commonly is seen in normal persons, is rarely appreciated on a real-time 2-D examination. Figure shows the usual labeling given to an M-mode mitral valve echogram.

One of the common uses of M-mode echocardiography is obtaining cardiac measurements. Figure 15 illustrates some of the M-mode measurements that are being used. The diastolic and systolic dimensions of the left ventricle can be used to calculate fractional shortening. One can also use an empirical formula to calculate volumes and provide ejection fraction. One can use M-mode dimensions for measuring septal and posterior wall thickness. These measurements can be combined to calculate left ventricular mass. Left atrial and aortic measurements are also commonly made with the M-mode examination.

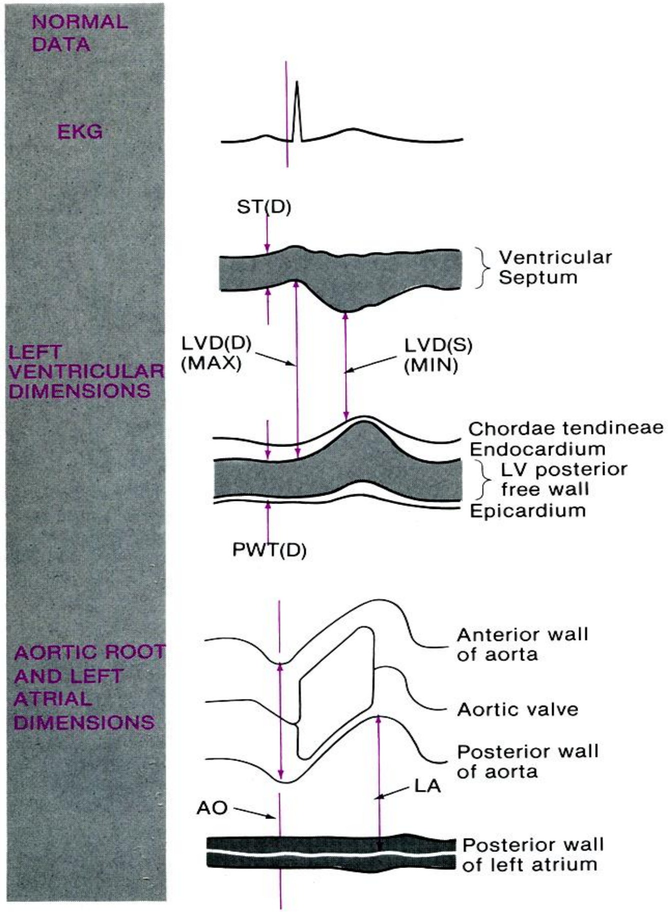

Fig.15. Methods for obtaining M-mode echocardiographic measurements. ST(D) = diastolic septal thickness; LVD (D) and LVD(S) = diastolic and systolic left ventricular diameters; PWT(D) = diastolic posterior wall thickness; AO = aorta; LA = left atrium.

Table 1 shows some of the M-mode measurements and normal values for these determinations.

Table 1. Normal values of M-mode echocardiographic measurements in adults.

	RANGE (CM)	MEAN (CM)	NUMBER OF SUBJECTS
Age (years)	13 to 54	26	134
Body surface area (M^2)	1.45 to 2.22	1.8	130
RVD—flat	0.7 to 2.3	1.5	84
RVD—left lateral	0.9 to 2.6	1.7	83
LVID—flat	3.7 to 5.6	4.7	82
LVID—left lateral	3.5 to 5.7	4.7	81
Posterior LV wall thickness	0.6 to 1.1	0.9	137
Posterior LV wall amplitude	0.9 to 1.4	1.2	48
IVS wall thickness	0.6 to 1.1	0.9	137
Mid IVS amplitude	0.3 to 0.8	0.5	10
Apical IVS amplitude	0.5 to 1.2	0.7	38
Left atrial dimension	1.9 to 4.0	2.9	133
Aortic root dimension	2.0 to 3.7	2.7	121
Aortic cusps' separation	1.5 to 2.6	2.9	93
Percentage of fractional shortening*	34% to 44%	36%	20%
Mean rate of circumferential shortening (Vcf)† or mean normalized shortening velocity	1.02 to 1.94 circ/sec	1.3 circ/sec	38

$$* \quad \frac{LVIDd - LVIDs}{LVIDd}$$

$$\dagger \quad \frac{LVIDd - LVIDs}{LVIDd \times \text{Ejection time}}$$

RVD = Right ventricular dimension
LVID = Left ventricular internal dimension; d = end diastole; s = end systole
LV = Left ventricle
IVS = Interventricular septum

DOPPLER ECHOCARDIOGRAPHY. Spectral Doppler echocardiographic recordings are basically of three types. There is the venous ventricular inflow and ventricular outflow pattern of Doppler flow (Fig. 16). Venous flow has both systolic and diastolic components. There will be some slight variation whether the recording is from systemic or pulmonary veins. There is frequently reverse flow that moves downward or away from the transducer following atrial contraction. Ventricular inflow is totally diastolic. There is an early component that peaks at the E wave and a late component following atrial contraction that peaks with an A wave. Ventricular outflow is entirely systolic in nature. Figure 16 shows the ventricular inflow or mitral flow pattern with the sample volume at the level of the mitral valve. One sees the early flow that peaks with the E wave and the late flow that peaks with the A wave, Figure 16 shows a pulsed Doppler recording of aortic flow taken with the transducer at the apex. With this “five chamber” view one sees the systolic flow moving away from the transducer during systole. Doppler flow patterns on the right side of the heart are essentially the same except the velocities are lower.

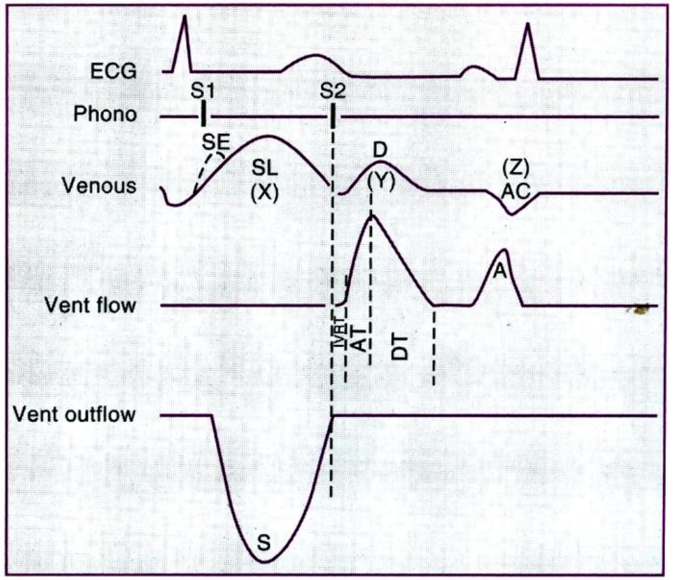

Fig. 16. Relationship between the electrocardiogram (ECG), phonocardiogram (PHONO), venous, ventricular inflow, and ventricular outflow Doppler velocities. SE = early systole; SL — late systole; D = diastole; AC = atrial contraction; IVRT isovolumic relaxation time; AT = acceleration time; DT = deceleration time.

HEMODYNAMIC INFORMATION. Doppler echocardiography is now the principal ultrasonic technique for obtaining hemodynamic information. By recording the velocity of intracardiac blood flow, one can obtain quantitative data concerning both blood flow and intracardiac pressures. The principle is illustrated in Figure 17. To calculate flow the mean velocity passing through an orifice or vessel and the cross-sectional area of the orifice or vessel must be known. The mean velocity is acquired by measuring the velocity time integral of the Doppler signal, which is the area under the recording. The cross-sectional area of the orifice through which the blood is flowing can be obtained directly with 2-D echocardiography; alternatively the diameter can be measured with either 2-D or M-mode echocardiography, and then the area can be calculated. Such flow determinations are feasible through any orifice or vessel.

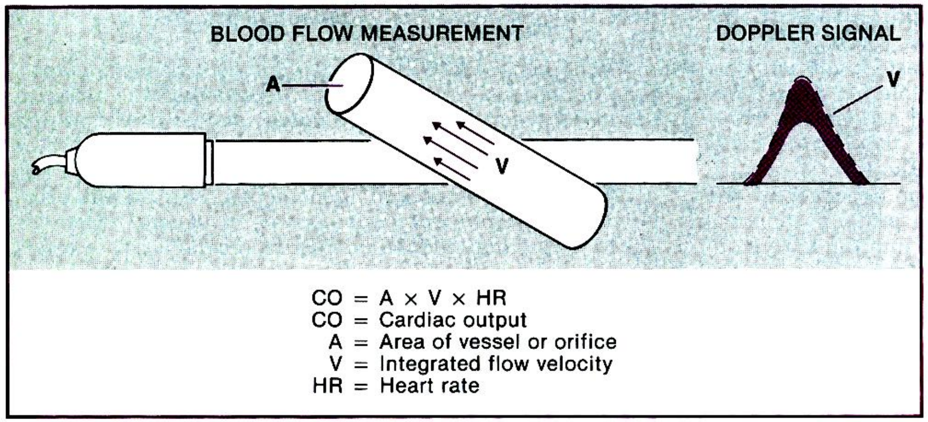

Fig.17. Principles of using Doppler echocardiography to measure blood flow.

DOPPLER MEASUREMENT OF PRESSURE GRADIENTS. Possibly the most important development in Doppler echocardiography has been the utilization of a modified version of the Bernoulli equation to calculate the pressure drop or gradient across a narrowed part of the cardiovascular system.

CLINICAL APPLICATIONS: THE ESTIMATION OF INTRACARDIAC PRESSURES. An early application of Doppler echocardiography was calculating a pressure gradient across a stenotic mitral valve. The approach was then used with stenotic semilunar valves.

DOPPLER MEASUREMENT OF VALVE AREA. Combining the Doppler principles for measuring blood flow and pressure gradient permits one to calculate a valve area utilizing the “continuity equation.” From blood flow calculations stroke volume is a function of the product of the integrated velocity with the area. The continuity equation states that the blood flow proximal to the area of obstruction must equal the blood flow passing through the area of obstruction. Thus, if the volume of blood proximal to an obstruction and the velocity of blood through the obstruction are known, the area of the stenotic orifice can be calculated. In the case of aortic stenosis the velocity and the area of the left ventricular outflow tract must be measured to calculate blood flow proximal to a stenotic valve. Then by measuring the velocity of flow across the valve the aortic valve area can be calculated.

ACQUIRED VALVULAR HEART DISEASE

Mitral Stenosis. The detection of mitral stenosis (MS) was the first clinical application of echocardiography. It remains an important technique in the evaluation of suspected mitral valve disease because echocardiography can allow visualization of the mitral valve in a manner not possible with any other procedure. The M-mode examination provides a sensitive assessment of the motion and thickness of the valve leaflets, while the 2-D technique provides a spatial image of the valve and allows direct measurement of the valve orifice. Doppler echocardiography provides hemodynamic assessment of the stenotic orifice.

Figure 18 shows an M-mode echocardiogram of a patient with calcific MS

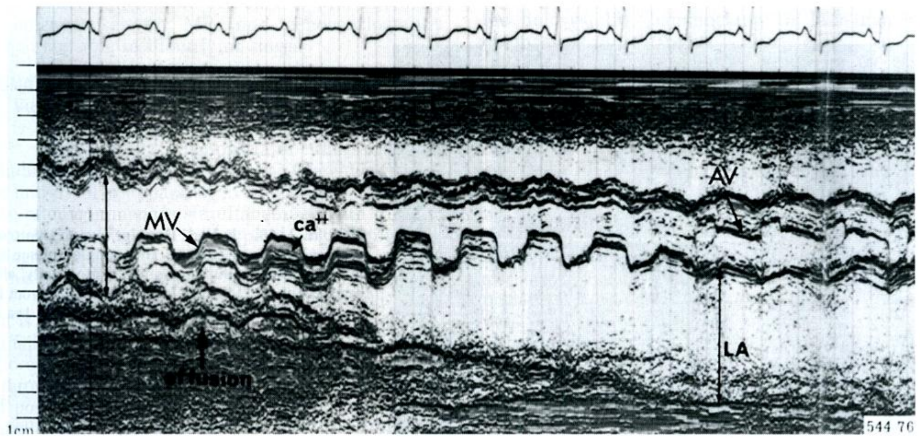

Fig.18. M-mode scan from a patient with mitral stenosis. The valve is calcified (Ca) and immobile. The left atrium (LA) is dilated, and there is moderate posterior pericardial effusion. AV = aortic valve.

The motion of the mitral valve is considerably altered from the normal pattern; the normal M-shaped configuration during diastole is no longer present, since the presence of a holodiastolic atrioventricular pressure gradient (diastasis) prevents rapid closure of the valve in mid-diastole. Although sinus rhythm was present, there was no reopening of the valve with atrial contraction and no A wave. Thus, the M-mode echocardiographic hallmark of MS is the absence of valve closure in mid-diastole and of reopening in late diastole. Although this decreased (flat) diastolic (E-F) slope is characteristic of MS, it is not specific. Other conditions such as decreased left ventricular compliance or low cardiac output may also reduce the diastolic slope of mitral valve motion.

Inadequate separation of the anterior and posterior leaflets of the valve occurs during diastole. Normally the two leaflets move in opposite directions during diastole, but when fused, as in MS, they do not separate widely and may actually appear to move in the same direction. The echocardiographic findings of reduced diastolic slope, increased thickness, and decreased separation of the valve leaflets provide a sensitive and accurate method for detection of MS.

The diagnosis of MS by 2-D echocardiography is made by noting thickening, doming, and restricted motion of the leaflets. Doming of any valve on 2-D echocardiography is a characteristic sign of stenosis. This distortion in shape with opening of the valve indicates that the tips of the leaflets are restricted in their ability to open, whereas the bodies of the leaflets still wish to accommodate more blood flow; thus the leaflets are curved, or domed. The presence of doming distinguishes a valve that is truly stenotic from one that opens poorly because of low flow. Two-dimensional echocardiography provides an opportunity to visualize and measure the flow-restricting orifice of the stenotic mitral valve directly.

Doppler echocardiography provides another means of quantitating the degree of MS. The peak velocities are increased, and the fall in velocity in early diastole is decreased. The technique for quantitating the degree of MS depends on the rate of velocity decrease in early diastole. The time interval required for the peak velocity to reach half of its initial level is related directly to the severity of the obstruction of the mitral orifice. This pressure half-time correlates reasonably well with the mitral valve area.

Mitral Regurgitation. DOPPLER ECIIOCARDIOGRAPHY. This is the ultrasonic procedure of choice for the detection of any valvular regurgitation. With this type of examination, high-velocity flow which aliases is recorded during ventricular systole in the left atrium.

Color flow Doppler is the principal echocardiographic technique for assessing the presence and severity of mitral regurgitation (MR).

Transesophageal echocardiography is more sensitive in detecting MR than is the transthoracic approach. The regurgitant blood flows into the left atrium during ventricular systole. The velocity is very high, and a mosaic, multicolored pattern is recorded because of aliasing. The location, direction, and size of the MR flow are readily depicted by the color flow system. There is a rough relationship between the size of the regurgitant jet and the extent of regurgitation, but this relationship is influenced by many factors, such as the direction of the regurgant jet

Aortic Stenosis. Doppler echocardiography has revolutionized the role of echocardiography and indeed the management of patients with aortic stenosis (AS). M-mode and 2-D echocardiography have always provided an excellent qualitative diagnosis of AS. Doppler echocardiography now provides an opportunity for the quantitative diagnosis. The 2-D echocardiographic diagnosis of valvular aortic stenosis is doming, thickening, and restricted motion of the leaflets. The valve may be heavily calcified and immobile, in which case only distorted, echo-producing, immobile valve leaflets are apparent. It is possible to make a semi-quantitative assessment of AS with 2-D echocardiography by judging the mobility of the leaflets, especially in the short-axis view. Although transthoracic 2-D echocardiography is rarely used to quantitate AS, there is renewed interest in using transesophageal echocardiography to measure the cross-sectional area of the aortic valve and thus quantitating AS.

The best ultrasonic technique for quantifying AS utilizes continuous-wave Doppler. Using the modified Bernoulli equation, it is possible to measure the pressure gradient across the aortic valve. There is an excellent relationship between the instantaneous gradient across the stenotic valve as measured by both catheterization and Doppler techniques.

Aortic Regurgitation. As with all valvular regurgitation, Doppler echocardiography is the examination of choice for detecting the presence of aortic regurgitation (AR). This type of examination is both sensitive and specific for the presence of AR. Color flow Doppler provides a 2-D display of the AR jet. The accuracy of Doppler flow mapping for quantitating AR is at best semiquantitative. The same limitations pertain to AR as were discussed with MR. The width of the aortic jet at the valve orifice as judged by color flow Doppler is used to judge the severity of

AR, and is clinically useful. The rate of decrease in velocity of the regurgitant blood as recorded in the left ventricular outflow tract using continuous-wave Doppler has been used as a reflection of severity of the AR. Severe AR produces a faster fall in velocity as the pressure difference between the aorta and left ventricle falls rapidly. AR can also be judged by the difference between aortic flow and pulmonary artery flow or mitral flow. One can calculate a regurgitant orifice size using Doppler continuity equation.

Tricuspid Regurgitation. This abnormality is also best determined by pulsed, continuous wave, or color flow Doppler echocardiography. As noted previously, the Doppler recording of tricuspid regurgitation can be used to estimate the pressure gradient across the tricuspid valve. This measurement provides an opportunity for estimating right ventricular systolic pressure by adding an estimate of right atrial pressure.

Two-dimensional echocardiography can help determine the etiology of tricuspid regurgitation. Rheumatic tricuspid regurgitation usually has an element of tricuspid stenosis and invariably exhibits MS. Pulmonary hypertension can be detected by estimating the right ventricular systolic pressure. Tricuspid valve prolapse gives an appearance similar to that of mitral valve prolapse A flail tricuspid valve is indicated by the finding of parts of the tricuspid valve protruding into the right atrium in ventricular systole. Carcinoid valve disease produces stiff immobile tricuspid leaflets that are continnously open. As with all valvular disease, transesophageal echocardiography can provide higher quality images of tricuspid valve pathology.

Secondary effects of tricuspid regurgitation can be noted on 2-D studies. Right ventricular and right atrial dilatation are invariably present. Abnormal diastolic motion of the interventricular septum indicates that right ventricular volume overload may be present.

ISCHEMIC HEART DISEASE•

DETECTION OF MYOCARDIAL ISCHEMIA. Two-dimensional echocardiography can detect ischemic myocardium by evaluating the motion, thickening, and thickness of various segments of the heart. Figure 19 shows diastolic and systolic frames in the long-axis and four-chamber views of a patient with ischemic heart disease. With systole the left ventricular cavity in both views becomes smaller. However, the

smaller cavity is a function of hyperkinesis of the posterior wall in the long-axis view and the lateral wall in the four-chamber view. The anterior and medial septum and apex (arrows) fail to move from diastole to systole. This akinesis is a result of inadequate blood flow within the left anterior descending artery. One of the advantages of the 2-D examination in patients with coronary artery disease is that the various myocardial segments correlate fairly predictably to coronary artery perfusion.

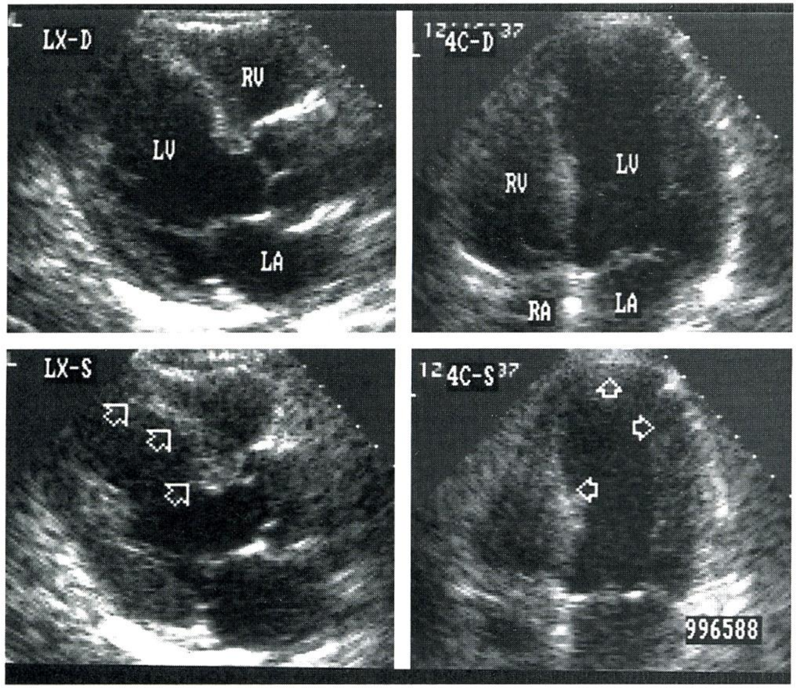

Fig.19. Long-axis (LX) and four-chamber 2-D echo- cardiogram of a patient with an anterior myocardial infarction secondary to occlusion of the left anterior descending artery. In systole there is akinesis (arrows) of the anterior system (LX-S) and distal septum, apex, and apical lateral wall (4C-S). LV = left ventricle; RV = right ventricle; LA = left atrium; RA = right atrium.

Figure 20 shows the relationship between four common 2-D echocardiographic views and the corresponding coronary artery perfusion. This diagram also shows the relationship between the short-axis view and the three longitudinal views (long-axis, two-chamber, and four-chamber). The recording of these four 2-D views can provide an excellent assessment of regional function in the setting of coronary artery disease.

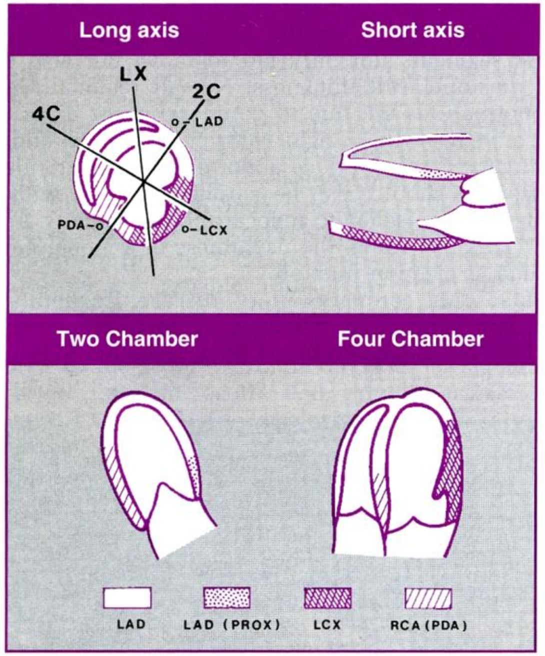

Fig.20. Relationship of 2-D echocardiographic views and coronary artery perfusion. 4C = four-chamber; LX = long-axis; 2C = two-chamber; LAD = left anterior descending; LCX = left circumflex artery; RCA = right coronary artery; PDA = posterior descending artery.

Another advantage of 2-D echocardiography is that with chronic ischemia and scar formation there is frequently loss of myocardial tissue as well as increased intensity of the echoes from that segment. Figure 21 shows a patient with a scarred distal septum and apex.

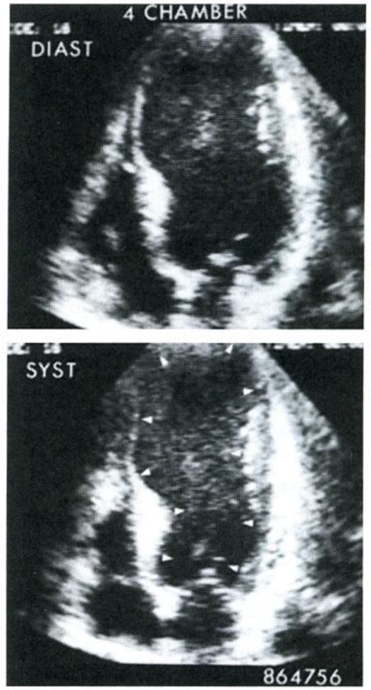

Fig.21. Apical four-chamber view in a patient with a scarred, dilated, aneurysmal apex and distal interventricular septum. The proximal half of the septum has normal thickness and contracts normally with systole.

The chronically ischemic segments not only fail to move but also exhibit loss of diastolic wall thickness. Not all regional wall-motion abnormalities are due to coronary artery disease. Left bundle branch block, right ventricular pacing, and open- heart surgery can produce abnormal interventricular septal motion. It should also be emphasized that with acute ischemia the nonischemic myocardium is usually hyperkinetic. This fact limits the usefulness of a global measurement such as ejection fraction.

Patients with coronary artery disease frequently have normal left ventricular function at rest. However, with stress there is inadequate blood flow, ischemia is produced, and the myocardium involved will stop moving.

CARD IDMYOPATHIES

HYPERTROPHIC CARDIOMYOPATHY (HCM). Echocardiography is an important diagnostic tool in patients with HCM and has enriched our understanding of this abnormality. An early echocardiographic abnormality to be noted was systolic anterior motion of the mitral valve (termed SAM) (Fig. 22), which appeared to be related to and was correlated with the presence of obstruction to left ventricular outflow. The shorter the distance between the septum and the leaflet and the longer the duration of apposition between these two structures, the more severe the obstruction.

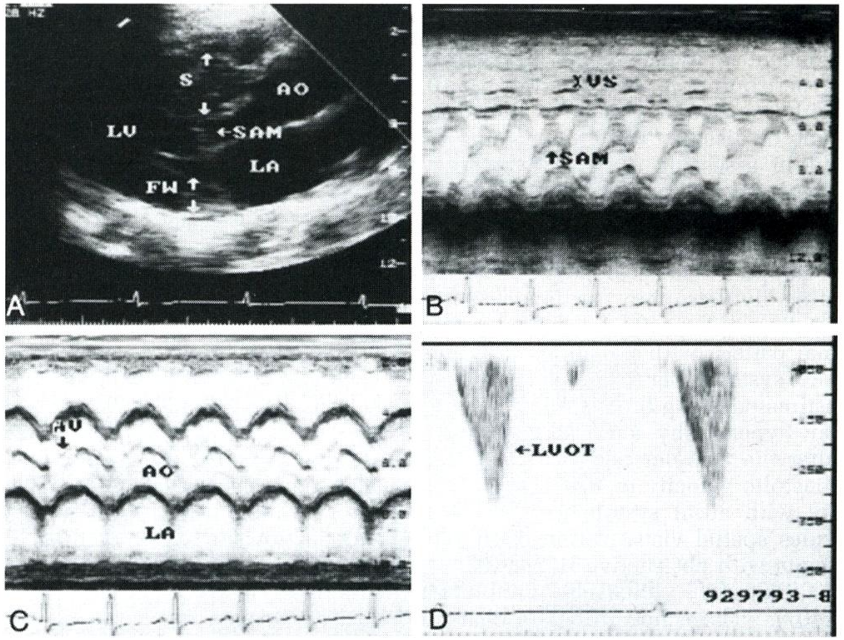

Fig.22. Two-dimensional, M-mode, and Doppler studies in a patient with hypertrophic obstructive cardiomyopathy. The 2-D long-axis study shows the thickened interventricular septum (5) and the systolic anterior motion of the mitral valve (SAM). The ahnormal mitral motion and the thickened septum are also seen on the M-mode recording (B) The M-mode recording of the aortic valve shows midsystolic closure (AV). The Doppler recording of the left ventricular outflow tract shows how the velocity within the outflow tract increases in the latter half of systole. LV = left

ventricle; AO = aorta; FW = left ventricular free wall; LA = left atrium; IVS = interventricular septum; LVOT = left ventricular outflow tract.

This echocardiographic finding also demonstrated the critical importance of involvement of the mitral valve apparatus in the obstruction in this condition.

A second echocardiographic finding in patients with obstructive HCM is midsystolic closure of the aortic valve (Fig. 22C). While this finding is not sensitive, when present it usually indicates a significant amount of obstruction.

Hypertrophy of the septum with abnormal organization of myocardial cells may be one of the basic abnormalities of HCM, and a key echocardiographic finding is disproportionate hypertrophy of the septum in relation to the posterior wall of the left ventricle, so that the ratio of thickness of the septum to the free wall exceeds 1.3:1.0 (Fig. 23) and the motion of the hypertrophied septum is reduced.

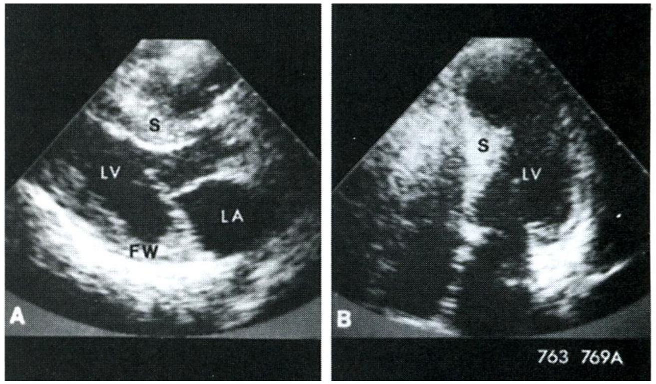

Fig.23. Long-axis (A) and apical four-chamber (B) echocardiograms of a patient with hypertrophic cardiomyopathy whose hypertrophy primarily involves the proximal two-thirds of the interventricular septum (5). The apex is spared from the hypertrophic process. LV = left ventricle; FW = left ventricular free wall; LA = left atrium.

It has also been shown that asymmetrical septal hypertrophy (ASH) is frequently transmitted as an autosomal dominant trait and that there are patients with asymmetrical septal hypertrophy who do not show SAM and therefore do not have obstruction to left ventricular outflow.

These patients may be considered to have HCM without obstruction. While the concept of recognizing ASH with or without obstruction to left ventricular outflow by echocardiography is an important one, there are limitations to echocardiographic diagnosis. First, the thickness of the septum may be difficult to measure precisely echocardiographically. Second, it must be appreciated that ASH is not pathognomonic for HCM and related myopathies and can occur in a variety of other disease states, including right ventricular hypertrophy. In addition, some patients with HCM may have concentric rather than asymmetrical hypertrophy, in which the septal and posterior left ventricular walls are equal in thickness.

CONGESTIVE (DILATED) CARDIOMYOPATHY. The echocardiogram characteristically reveals a dilated poorly contracting left ventricle in patients with congestive cardiomyopathy. Signs of reduced cardiac output include a poorly moving aorta, reduced opening of the mitral valve, and slow closure of the aortic valve. The left atrium is dilated, and the abnormal closure of the mitral valve indicative of elevated left diastolic pressure is frequently noted. Incomplete closure of the mitral valve or papillary muscle dysfunction and subsequent mitral regurgitation are common. Left ventricular filling on Doppler echograms changes as the disease progresses. It must be appreciated that these findings are nonspecific and may also occur in patients with ischemic heart disease. However, at least one portion of the left ventricle continues to exhibit normal motion in most, although not all, patients with severe coronary artery disease. In patients with cardiomyopathy the impairment of left ventricular wall motion is diffuse.

PERICARDIAL DISEASE

PERICARDIAL EFFUSION. The theory underlying the use of ultrasound in the recognition of pericardial effusion is relatively simple; since the acoustic properties of fluid differ significantly from those of cardiac muscle, the effusion surrounding the heart is less echogenic than is the myocardium. Accordingly, the detection of effusion was one of the first and has remained one of the most useful applications of echocardiography.

Figure 24 shows a 2-D echocardiographic examination of a patient with a large pericardial effusion (PE). One can see the echo-free space

both anteriorly and posteriorly in the long-axis (A) and short-axis (B) views. The four chamber view (D) shows the fluid on both the medial and lateral aspects of the heart. There is very little if any fluid posterior to the left atrium (A and C). The size of the effusion is estimated by the amount of echo-free space surrounding the heart. Frequently with small effusions one sees only a posterior echo-free space and very little fluid anteriorly. As the fluid increases it distributes both anteriorly and posteriorly. With large effusions, as in Fig. 24, one usually sees more anterior fluid than posterior fluid as the heart tends to sink posteriorly.

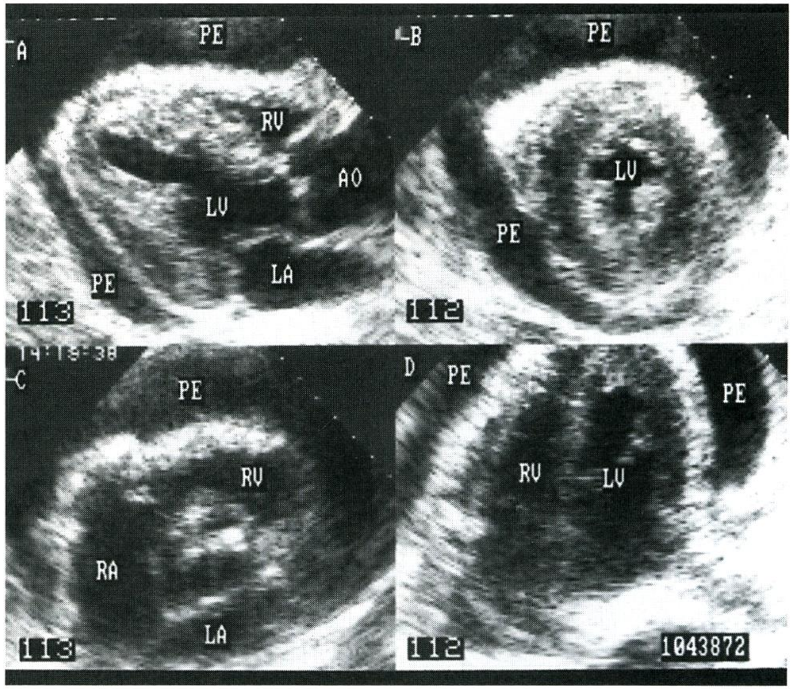

Fig.24. Long-axis (A), short- axis at the papillary muscle (B), short- axis at the base of the heart (C), and apical four-chamber (D) 2-D echocardiograms of a patient with a large pencardial effusion (PE). the relatively echo-free fluid can be seen surrounding the heart in all views. The visceral pencardium is echogenic and probably thickened. RV = right ventricle; LV = left ventricle; AO = aorta; LA = left atrium; RA = right atrium.

CARDIAC TUMORS AND THROMBI

LEFT ATRIAL TUMORS. Left atrial myxoma is by far the most common cardiac tumor, and echocardiography has proved to be an extremely important diagnostic technique for its recognition.

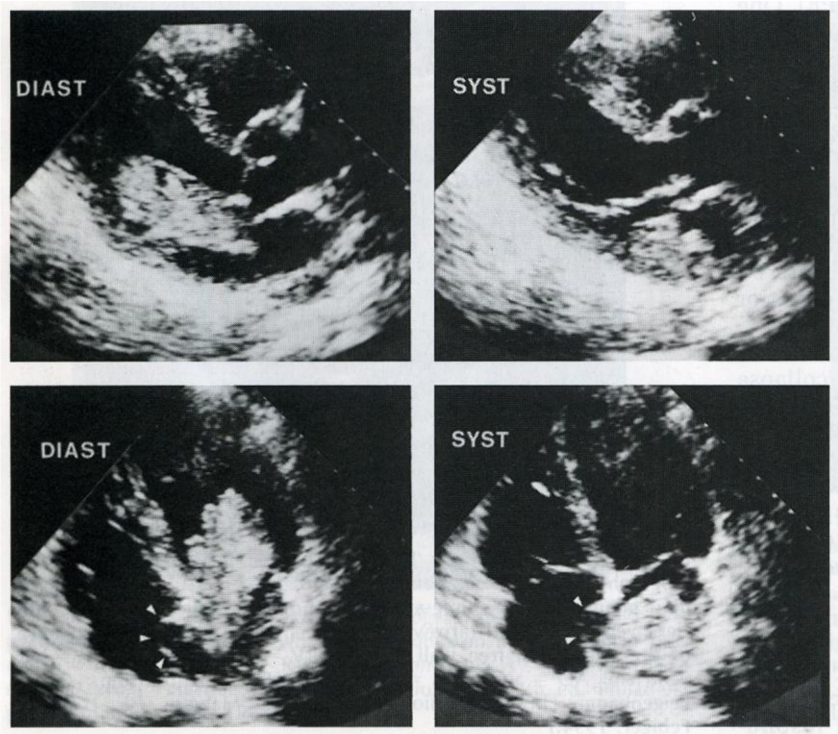

Fig.25. Long-axis (top) and apical four chamber (bottom) 2-D echocardiograms in diastole and systole in a patient with a left atrial myxoma and ar atrial septal aneurysm. The septal aneurysm (arrow heads) can be seen bulging toward the right atrium ir both diastole and systole in the four-chamber view.

The spatial orientation inherent in this examination provides additional useful information, and the size and shape of the mass are apparent. In addition, the site of attachment of the mass to the cardiac structure can frequently be detected. Transesophageal echocardiography

provides an outstanding view of the left atrium and has vastly improved our ability to detect all intracardiac masses. Excellent definition of left atrial masses can be seen with this unobstructive view. Figure 25 shows four images of a small left atrial mass that is attached to the interatrial septum (lAS). Although this tumor was seen on a transthoracic 2-D echocardiogram, the clarity and detail were greater with the transesophageal examination.

LEFT ATRIAL THROMBI. Other space-occupying structures — atrial thrombi—have been identified in the left atrium by means of echocardiography. Since most are located near the left atrial appendage, transesophageal echocardiography is superior to conventional echocardiography in visualizing left atrial thrombi. The transesophageal technique may detect spontaneous contrast in the left atrium, which is frequently associated with and may be a precursor of thrombus formation.

RIGHT ATRIAL MASSES. Right atrial myoma is not as common as the left atrial variety. Such tumors can also be detected echocardiographically. They appear as a mass of echoes that are in the right atrium during systole and traverse the tricuspid valve during diastole. As on the left side of the heart, a large vegetation involving the tricuspid valve can simulate a right atrial myxoma. Bilateral atrial myxomas have been detected echocardiographically. Right atrial thrombi that have the potential of producing massive pulmonary emboli have been detected with 2-D echocardiography.

VENTRICULAR TUMORS. Myomas can occur in the ventricles as well as in the atria and have been imaged in both ventricles. When the tumors are mobile, they can produce very dramatic echograms on both M-mode and 2D examinations; they may move above the mitral valve into the left ventricular outflow tract during systole. Pedunculated right ventricular masses can prolapse into the pulmonary artery or simulate pulmonic stenosis. Rhabdomyomas and fibromas can also involve the ventricles; these two types of lesions have been imaged successfully.

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