Textbook of
Two-Dimensional Echocardiography

Edited by

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Preface

The widespread application of two-dimensional echocardiography has expanded the practice of cardiac ultrasound dramatically since 1978. The two-dimensional technique has been incorporated into many aspects of the noninvasive evaluation of patients with known or suspected heart disease; in addition, new areas of application are being developed, such as tissue characterization, three-dimensional spatial reconstruction, and Doppler and contrast echocardiography. With two-dimensional echocardiography gaining such acceptance as a noninvasive imaging technique, we felt it important to include in one textbook both the many established clinical uses and the more recently developed aspects of the technique.

To be most effective in presenting the large volume of information now available about two-dimensional echocardiography, we invited additional experts in the field to prepare chapters about the state of the art. Although differences in style are unavoidable in chapters written by different authors, we have attempted through diligent editing and updating to maintain a uniformity of purpose and style throughout the text. Any shortcomings resulting from differences in style, however, are more than compensated by the knowledge and experience contributed by these authors.

The book begins with a discussion of the historical development of two-dimensional echocardiography. We believed it was important to begin with an overview of the early development of two-dimensionl echocardiography and to include descriptive and graphic material that outline basic principles used in its daily application. A detailed discussion of the principles and physics of ultrasound is not included, since it is outside the scope of this text and has been well described in other books.

In Chapter 2 anatomic slice specimens of normal hearts are presented and compared with tomographic slices of standardized two-dimensional views. Although references are made to other conventions of nomenclature and display, Chapter 3 lists in detail the standards published by the American Society of Echocardiography (ASE).

The next three chapters systematically consider the normal and abnormal two-dimensional echocardiographic findings related to the mitral valve (Chapter 4), the aortic valve and thoracic aorta (Chapter 5), and the right heart, including the tricuspid and pulmonic valves, right atrium, and right ventricle (Chapter 6). The discussion of echocardiography of valvular heart disease concludes with a chapter on the usefulness of two-dimensional echocardiography in evaluating prosthetic heart valves (Chapter 7).

Two-dimensional echocardiography is then considered in terms of its efficacy in assessing normal and abnormal myocardium. Specifically, there are clear and concise discussions about measuring right and left ventricular volumes (Chapter 8), ischemic heart disease and its complications (Chapter 9), and the hypertrophic, congestive, and restrictive cardiomyopathies (Chapter 10). These discussions are followed by chapters on diseases of the pericardium (Chapter 11); cardiac masses, tumors, and thrombi (Chapter 12); and the use of echocardiography in congenital heart disease (Chapter 13).

Since no serious discussion of two-dimensional echocardiography is complete without presenting the newer developments, we have included chapters that focus on new applications in contrast echocardiography (Chapter 14), the principles and uses of Doppler echocardiography (Chapter 15), three-dimensional echocardiography (Chapter 16), and tissue characterization (Chapter 17). The last chapter discusses the role of two-dimensional echocardiography in the context of other established and newer cardiac imaging techniques, including digital subtraction angiography, computerized axial tomography, and radionuclide imaging techniques, particularly positron emission tomography and nuclear magnetic resonance.

Although there are references to M-mode echocardiography and appropriate M-mode figures are used throughout the text, this work deals primarily with two-dimensional echocardiography. We have not attempted to present a comprehensive review of M-mode echocardiography, as this has already been well covered in other textbooks of echocardiography. It should be noted that a companion workbook—*Cardiac Ultrasound Workbook,* edited by James V. Talano, M.D., New York, Grune & Stratton, 1982—is designed to be of assistance to those who would like more instruction about the technique of properly performing and interpreting M-mode and two-dimensional echocardiograms.

We hope that the numerous illustrations and bibliographic references presented in this work will be useful to the reader as a reference source and as a stimulus to additional study of two-dimensional echocardiography.

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Contents

CHAPTER 1

History and Instrumentation

Julius M. Gardin and James V. Talano

EARLY HISTORY OF CARDIAC ULTRASOUND

The engineering principles used for diagnostic ultrasound have their origins in the latter half of the 19th century and the early part of this century. An early development was Galton's ultrasonic whistle in 1883, which was capable of generating vibrations with frequencies as high as 25,000 cycles per second. The advent of submarines during World War I became the impetus for developing ultrasound devices that were capable of detecting underwater objects. Langevin, in France, using a quartz crystal, developed a method of generating and transmitting ultrasound waves through water. The First World War, however, ended before an ultrasound device capable of detecting submarines could be built.

Between the First and the Second World War, much basic research into the properties and applications of ultrasound technology was performed. The speed of ultrasound transmission was determined in various human tissues. Ultrasound technology was applied to underwater depth measurements, to monitoring movement of dolphins and whales, and to detecting flaws in metal. The Second World War spurred the development of electronic instrumentation for military use. Radar applications required advanced technology in recording brief energy pulses and measuring extremely short transit times. An outgrowth of this technology was the adaptation of the oscilloscope to measure brief electronic events. In addition, the widespread use of ultrasound or sonar in detecting submarines was responsible for the increased knowledge of ultrasonic transducer technology.[1]

After World War II, nonmilitary use of ultrasound expanded rapidly. Firestone, in the United States, developed the first nondestructive flaw-detector for testing of metals.[2,3] His utilization of pulsed–reflected ultrasound for material-testing stimulated much interest in ultrasound for medical diagnostic use. In the late 1940s and early 1950s, American and European investigators began imaging cross-sections of the human body, including the heart. Keidel transmitted and recorded ultrasound waves through the heart in an attempt to determine cardiac volumes.[4] Hertz and Edler were the first investigators to examine the heart utilizing Firestone's pulsed–reflected ultrasound. Initially they used the Firestone device to record echoes from the back wall of the heart,[5] but eventually they were able to record an echo signal returning from the anterior mitral valve leaflet.[6,7]

The detection of mitral stenosis, pioneered by Edler and associates, was the foremost early clinical application of single-dimensional (both A-mode and M-mode) echocardiography. Other uses included detecting left atrial tumors, anterior pericardial effusion and aortic stenosis.[6,8] Effert and associates,[9,10] in Germany, and Joyner and Reid,[11] in the United States, confirmed the utility of single-dimensional ultrasound in detecting mitral stenosis. Other significant early advances in the use of single-dimensional echocardiography were the detection of pericardial effusion, described by Feigenbaum and associates,[12,13] and visualization of intracardiac echoes utilizing indocyanine green dye, reported by Gramiak and associates.[14]

DEVELOPMENT OF TWO-DIMENSIONAL ECHOCARDIOGRAPHY

Several different methods of producing two-dimensional (cross-sectional) echocardiograms were developed beginning in the late 1960s. Each technique reconstructed the two-dimensional cardiac image from multiple B-mode scan lines. In B-mode scans the reflected ultrasound signal is converted from a spike to a dot—the brightness of the dot reflecting the amplitude of the echo spike. With electronic tracking of the transducer, a spatially oriented two-dimensional image can then be created.

One classification categorizes two-dimensional systems as to their transducer location and beam angle, e.g., sector, linear, arc, or compound scans (Figure 1-1).

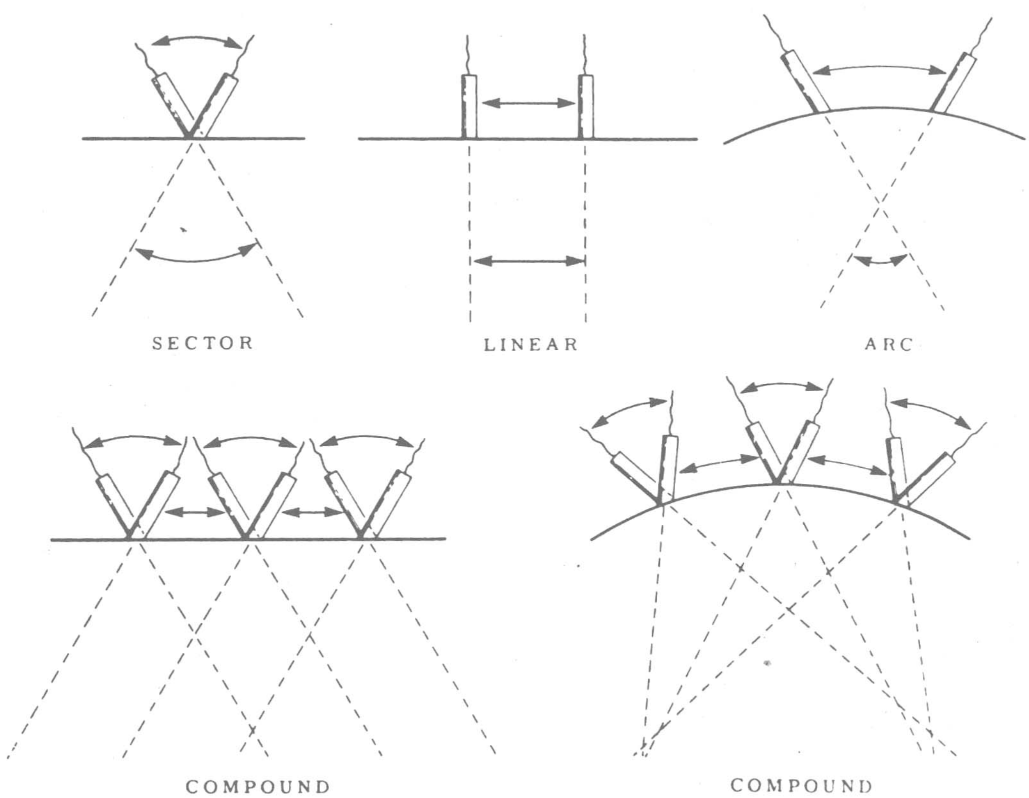


Figure 1-1. Types of scans utilized to obtain two-dimensional images. (From Feigenbaum H (ed): Echocardiography (ed 2). Philadelphia, Lea & Febiger, 1976. With permission.)

The most common scan used in examining the heart is the sector scan, where the transducer itself remains stationary with only the angle of the emitted ultrasound beam being changed. A linear scan, on the other hand, involves changing the transducer position but holding the beam angle constant. An arc scan is similar to a linear scan except that the transducer surface is curved so that the individual ultrasonic beams are not parallel and eventually cross within the organ being scanned. This type of scan is rarely used in echocardiography but is frequently used in ultrasound examination of the breast. Compound scanning is merely a combination of two or more of these basic scan types—e.g., a sector scan with a linear scan.[15]

Another classification for two-dimensional systems divides them into (1) composite—in which the two-dimensional image is a compilation of B-mode scan lines obtained from a number of cardiac cycles[15]; and (2) real-time—in which individual scans of the heart are obtained so rapidly that cardiac motion can be viewed directly.

A number of earlier approaches to two-dimensional echocardiography involved the use of composite B-mode scanning.[16–18] In this technique, the image produced is not real-time, since multiple cardiac cycles are required to develop an image. Ultrasound signals from cardiac structures are obtained by utilizing a standard M-mode echocardiographic system whose transducer is attached to a potentiometer capable of indicating the orientation of the transducer in space. The signals obtained are displayed vertically as dots whose depth and brightness are proportional to the distance of the target from the transducer and the amplitude of the signal, respectively. In M-mode echocardiography, these vertical ultrasound signals are swept across the horizontal axis with time. Conversely, in B-mode scanning, the multiple scan lines obtained are displayed at a position analogous to their spatial orientation and then combined to form a composite cardiac image.

During a cardiac cycle, however, there is significant translation of the heart in space. It is therefore necessary in the B-mode technique to obtain ultrasound signals only at a selected period during the cardiac cycle. This selection of images at specific times during the cardiac cycle is made possible by electrocardiographic gating—i.e., triggering the collection of images at specific intervals during the QRS and T waves of the EKG. Teichholz and associates[18] demonstrated the utility of B-mode scans in evaluating left ventricular anatomy and function.

Real-time two-dimensional sector scans can be performed by either mechanically or electronically steering the ultrasound beam through an arc ranging from 30° to 90°. A historical approach will be utilized to describe first the mechanical sector scanners and then the electronic linear-array and phased-array scanners. Figure 1-2 depicts the more common real-time scanners that are in use.

MECHANICAL SECTOR SCANNERS

The water bath and mirror system scanners were early types of mechanical sector scanners. One of the first attempts at clinical two-dimensional mechanical cardiac imaging was described by Ebina and associates in 1967.[16] Their approach utilized a water bath B-scanner that obtained either compound B-scans gated at a portion of the cardiac cycle or a real-time sector scan obtained by mechanically rotating the transducer within the water bath. Figure 1-3 demonstrates this early water bath real-time mechanical scanner and Figure 1-4 demonstrates images that were obtained utilizing this system.

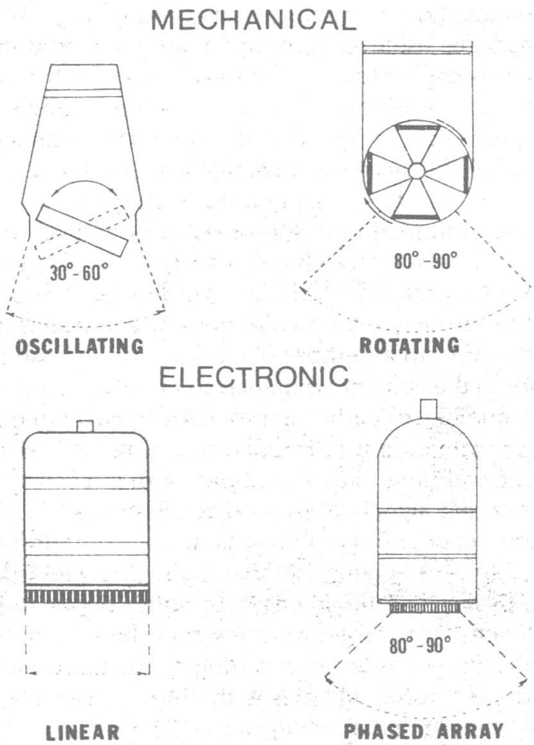
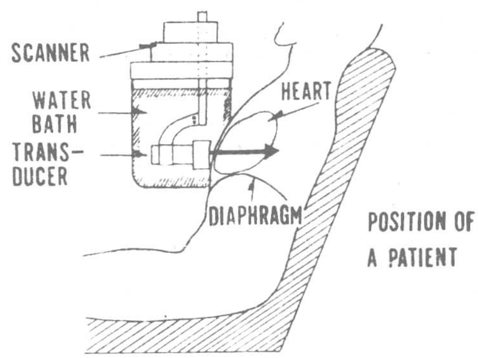


Figure 1-2. Diagrammatic representation of four common types of real-time scanners used in two-dimensional echocardiography.

Another early attempt at sector scanning was the cinematographic technique described by Asberg in 1967.[19] This approach involved a reciprocating mirror system containing two reflectors and two transducers that resulted in a two-dimensional image at a rate of seven frames per second. A different method of mechanical sector scanning, developed by Flaherty and associates, used an ultrasonic scanner in conjunction with a fluoroscopic image.[20] The system was capable of locating both the ultrasonic transducer and the anatomic cross-section being explored; furthermore, this unit was capable of framing rates of 40 frames per second and generated ultrasonic sectors up to 30°. Patzold and associates developed a device that rotated a sound source around the focal lines of a cylindrical parabolic mirror and produced

Figure 1-3. Early real-time sector scanner that obtained images by mechanically rotating a transducer within a water bath. Either gated compound B-scan images and real-time sector scan images could be obtained. (From Ebina T, Oka S, Tanaka M, et al: The ultrasonotomography of the heart and great vessels in living human subjects by means of the ultrasonic reflection technique. Jpn Heart J 8:331, 1967. With permission.)



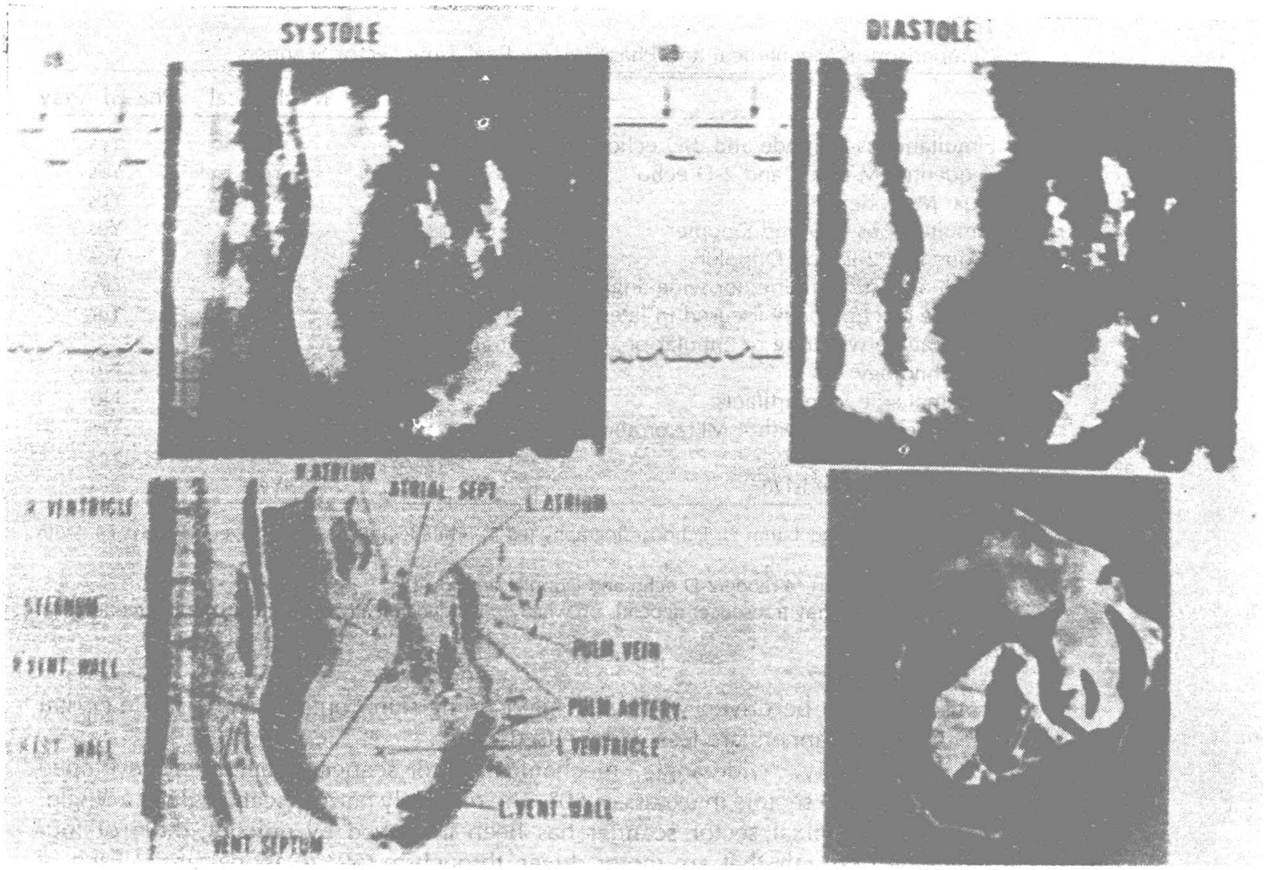


Figure 1-4. Real-time two-dimensional images obtained with a water bath mechanical sector scanner as seen in Figure 1-3. (From Ebina T, Oka S, Tanaka M, et al: The ultrasonotomography of the heart and great vessels in living human subjects by means of ultrasonic reflection technique. Jpn Heart J 8:331, 1967. With permission.)

a rectangular ultrasound scan at a framing rate of 15 frames per second.[21] Hertz and Lindstrom reported the use of a water bath sector scanner that allowed cardiac imaging at a rate of 16 frames per second.[22]

The next major development was Griffith and Henry's mechanical sector scanner, which utilized a single transducer that oscillated rapidly through a 30° sector.[23] Thirty frames or sectors, each containing two fields, were produced each second. Since the pulse repetition frequency was 2000 Hz, each of the 30 separate frames consisted of 66 ultrasound scan lines. Eggleton and associates[24] developed a 30° sector scanner capable of producing 60 frames per second. As in B-mode scanning, electric potentiometers were attached to the transducer to depict the orientation of the individual B-mode scan lines analogous to their spatial orientation.

The advantages of the single transducer mechanical sector scanners include their relative inexpensiveness, portability, simplicity in engineering, compatibility with high-frequency transducers, excellent signal-to-noise ratio, and high line density (Table 1-1).[40] The disadvantages are the minor discomfort experienced by the patient from the oscillation of the transducer on the chest wall and the limited 60° sector scan. The narrow sector is due to the limitation of the arc through which the ultrasonic

Table 1-1
Comparison of Mechanical and Phased-Array Real-Time Sector Scanners

	Mechanical	Phased-Array
Simultaneous M-mode and 2-D echo	No*	Yes
Sequential M-mode and 2-D echo	Yes	Yes
Dual M-mode echo	No	Yes
Simultaneous 2-D and Doppler	No*	Yes
Sequential 2-D and Doppler	Yes	Yes
Small acoustic window for wide-angle scan	No	Yes†
Can be electronically focused in lateral (y) axis	No	Yes
Compatible with ring or annular phased-array transducer technology	Yes	No
Minimal side-lobe artifacts	Yes	No
Easily compatible with 4 MHz or above	Yes	Yes
Portable	Yes	Yes
Relatively inexpensive	Yes	No

Adapted from Feigenbaum H: Echocardiography (ed 3). Philadelphia, Lea & Febiger, 1981, p 18. With permission.
*Near-simultaneous M-mode/2-D echo and Doppler are possible.
†Size of phased-array transducer depends on whether it is dynamically focused and on the frequency of the transducer.

transducer can be driven while still maintaining skin contact. Thus, single-crystal mechanical scanners are less widely used today.

More recently, "wide-angle" mechanical sector scanners have been developed which produce sectors in excess of 80°. The relatively narrow scan angle of a single-crystal mechanical sector scanner has been improved by utilizing three or four ultrasound crystals that are motor driven through a 360° rotational arc.[25] Each of the individual transducers provides ultrasonic scan lines for only a quarter segment of its 360° rotation—i.e., 80°–90°. The crystals are not in contact with the skin; they are enclosed within a plastic housing in oil. In addition to providing a wider scan angle than does a single oscillating crystal, this device has the advantage of not producing any vibratory discomfort for the patient. It also provides a wider imaging angle and more evenly distributed line density. Potential disadvantages of such a multitransducer system are (1) the plastic housing may result in inferior ultrasound images due to attenuation of the ultrasound signal by the plastic or the air bubbles within the oil, (2) reverberation artifacts may also be produced from the plastic housing, and (3) image degradation may occur from "cross-talk" interference between transducer elements that are mismatched—i.e., have different acoustic properties.

LINEAR-ARRAY TECHNIQUES

The linear-array ultrasound scanner was another early development in real-time two-dimensional cardiac imaging.[26–31] The first linear-array scanner, described by Bom and associates in Holland in 1971, featured a row of 20 standard M-mode piezoelectric crystals electronically excited to emit ultrasound in a sequential manner.[26] Later systems utilized up to 64 single transducers producing a rectangular two-dimensional image whose overall size was dependent on the size of each transducer.