ULTRASONIC TWO-DIMENSIONAL IMAGING OF THE HEART WITH MULTISCAN

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To Martine,
   Piet, Raf and Eva
To My Parents

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The author is greatly indebted to all friends and colleagues who directly or indirectly contributed to the realization of this thesis.

CONTENTS

CHAPTER 1

PURPOSE OF THE STUDY - A BRIEF SKETCH

The introduction of the prototype of an ultrasonic linear array scanner in 1971, confronted us with a type of diagnostic information which was different from conventional cardiac imaging techniques. With the use of ultrasound, cardiac structures were now displayed in a direct and positive manner rather than as shadows or negative impressions in contrast media as seen with X-ray and angiocardiographic techniques. Imaging in multiple new planes through the heart now became possible. These planes were difficult or impossible to visualize with other techniques. Therefore hardly any knowledge about the anatomic information in these images existed. The major aim of this thesis is to present the implementation into the clinical practice of cardiology of the linear array system which was developed at the Thoraxcenter in Rotterdam.

The chapters 2-4 introduce the ultrasonic method and give some background for the reader not entirely familiar with cardiac ultrasound. Chapters 5-7 describe the first clinical results, the progress in examination technique, and potential applications. Indeed, our first concern was to establish standardized transducer positions on the chest wall to produce consistent results and to identify the cardiac structures in these various cross-sections. These clinical studies were also necessary to investigate which cardiac abnormalities could be best studied with this new method. Their publication created considerable interest in real time cross-sectional analysis of the heart all over the world.

The new technique allowed one to obtain information about ventricular size, shape, wall dynamics, and a measurement of both the long axis and surface area of the left ventricle. Thus, quantitation of left ventricular performance was attempted by applying formulae largely tested on quantitative single plane angiocardiography. Initial results in a small series of patients were promising and are given in chapter 8. However, the poor correlation coefficient and the large standard errors found in a series of 50 consecutive patients studied subsequently (chapter 9) indicated that a reliable relation was not present in all conditions.

In addition, there was a low success rate in obtaining the necessary cross-sections for quantitative analysis. The reasons for these unsatisfactory clinical results were analysed and published in 1976. Its content constitutes chapter 10.

The first clinical results with the dynamic focused linear array system, yielding a better quality image, were published in 1977. However, the success rate in obtaining the required good quality images for quantitative analysis of the left ventricle was still too low to consider repeating the studies. Thus, further efforts were made to evaluate the potential of the method in obtaining qualitative diagnostic information about cardiac structure orientation and dynamics.

One interesting method which complements the ultrasonic imaging capabilities is the use of the echo contrast. The peripheral venous injection of e.g. dextrose 5% in water produces dense clouds of echoes in the blood and hence allows one to observe the blood flow through the right sided cardiac cavities. The contrast method requires good quality images and offers the unique potential of noninvasively demonstration of intracardiac right to left shunts. Our experience with this new

diagnostic application is described in chapter 11.
The availability of electronic integration techniques and a small display monitor recently made it possible to construct a miniature hand-held and battery-powered real time scanner. After favorable initial clinical experience,detailed in chapter 12, the device has been extensively tested in an attempt to establish its potential clinical applications in cardiology (chapter 13).
This thesis is completed by a discussion of the present status of ultrasonic cardiac imaging with the author's personal view on the future (chapter 14).

CHAPTER 2

INTRODUCTION TO M-MODE AND TWO-DIMENSIONAL ECHOCARDIOGRAPHY

Among the new diagnostic methods in cardiology, cardiac ultrasound is certainly one of the most informative and intriguing. Its major advantage is early diagnosis and clinical insight into advanced-treatment techniques.
The technique was introduced in Sweden by Edler and Herz in the early fifties (1). Its clinical application remains a striking example of productive interaction between cardiologists, physicists, and industry (2). The single-element ultrasonic systems consisted of a piezoelectric transducer driven by pulse-echo transmit receive electronics. A time-motion display of intensity-modulated echoes representing cardiac structures versus depth can thus be obtained (M-mode echocardiography). The method, however, did not immediately find widespread acceptance by cardiologists. Reasons for this were mainly technical, especially the sensitivity of the systems and the lack of appropriate recorders. This situation changed dramatically in the late sixties when more sensitive instruments and more importantly, strip chart recorders became available. These developments stimulated improvements in examination techniques and allowed a more accurate interpretation of the recordings and hence, a more relaible diagnosis of a wide variety of cardiac diseases. This resulted in an explosive interest in the method and the rapid acceptance of M-mode echocardiography as an effective method for cardiac diagnosis. This widespread use also demonstrated the specific limitations of the use of a single sound beam and the need for two-dimensional cardiac imaging methods. When these instruments became available in the early seventies, they further accelerated the application of cardiac ultrasound. This chapter will provide a rather broad view of the underlying principles of both M-mode and two-dimensional echo-

cardiography and an appreciation of the type of information they provide.

2.1 ULTRASOUND BASICS

Ultrasound refers to sound waves with a frequency above the range audible to man (20.000 Hertz). In cardiology, frequencies ranging from 2 to 7 MegaHertz (MHz) are employed. These sound waves are propagated as longitudinal vibrations at a velocity determined by the molecular structure of the medium through which they pass. To generate such ultrahigh frequency sound waves, piezoelectric crystalline material is used which converts electrical energy to mechanical (ultrasound wave) energy and vice versa.

Such crystals form the core of the ultrasonic transducer. The diagnostic value of ultrasound waves is the result of partial reflections of these waves when they strike boundaries between media of different acoustic impedance (defined as the velocity of sound transmission x density). The returning sound energy on the transducer is converted to an electrical impulse which can be displayed for analysis. The elapsed time from transmission of the sound to reception of the echo is measured to convert this time into distance relative to the transducer. Assuming a constant speed of 1580 meters/sec for sound in soft biologic tissue, the time for a round trip from transducer to reflecting surface indicates the distance. In fact, part of the sound energy is reflected from each subsequent tissue interface along the sound beam pathway and distance measurements to all echoproducing interfaces encountered are available from individual pulses. The greater the difference in acoustic impedance between the media, the greater the amount of energy reflected. The intensity of the echoes is further dependent upon the angle at which the sound beam strikes the boundary and energy attenuation with increasing distance. Since ultrasound does detect minor tissue differences, soft tissue structures can be outlined in a manner not possible with conventional radiologic methods.

Most instruments transmit ultrasound during 1 microsecond and receive echoes for the next 999 microseconds yielding a repetition rate of 1000/sec. Because of this high repetition rate, resolution in time is excellent and the motion analysis of cardiac events is more precise than with cineangiographic techniques.

The relation between the velocity of sound which is approximately constant in biologic tissue, wave length and frequency (velocity = wave length x frequency) dictates that wave length decreases with higher frequencies. The pulse length determines the axial resolution or ability to resolve two adjacent structures aligned along the sound beam axis. Short pulses are more easily created when using higher frequencies. Unfortunately there is a reciprocal relationship between resolution and depth penetration. The ultrasonic frequency employed must therefore be a compromise between these two objectives.

Ultrasonic sound waves of a relative low frequency (2.25 MHz) penetrate to deep structures and are used in adults. In contrast, higher frequencies (5 - 7 MHz) with a better axial resolution but less penetration are used in paediatric applications. The width of the ultrasonic beam determines the lateral resolution or ability to distinguish two adjacent structures in the directions perpendicular to the sound beam axis. Beam width is a function of the transducer size and the frequency at which it operates. As the ultrasound beam is formed its width does not change over a certain distance termed the near field and then begins to diverge in the far field. In the near field, the beam width is approximately equal to the active surface of the transducer. The latter can be selected relatively "small".

The narrow beam and concentrated energy make the near field therefore desirable for recording. The length of the near field is determined by the relationship: near field length = transducer radius squared divided by wave length. Thus decreasing the size of the transducer will decrease the near field length and using lower frequencies will have the same effect. Beam divergence in the far field is calculated from equation; Sin Ø = 1.22 x wave length divided by transducer diameter. It is apparent from this equation that beam divergence increases with smaller crystals and lower frequencies. Beam divergence is an important factor and degrades the accuracy for examining structures in the far field by limiting the lateral resolution. A wide beam causes superimposed echoes of laterally spaced targets on the display and may pose serious problems in correct interpretation of clinical echocardiograms. A partial solution to delay divergence of the beam is to use acoustical lenses. Unfortunately, the segment of the beam in focus where the resolution is good, is not very long. Therefore, transducers focussed at 5,7 or 10 cm are available for more accurate data acquisition at the focal length indicated.

The power density used in diagnostic ultrasound systems is well within known limits of safety (3,4). At present there is no clinical evidence of hazard associated with ultrasound examination.

2.2 M-MODE ECHOCARDIOGRAPHY

The echoes received by the transducer are electronically processed to produce three types of oscilloscope display (figure 1).

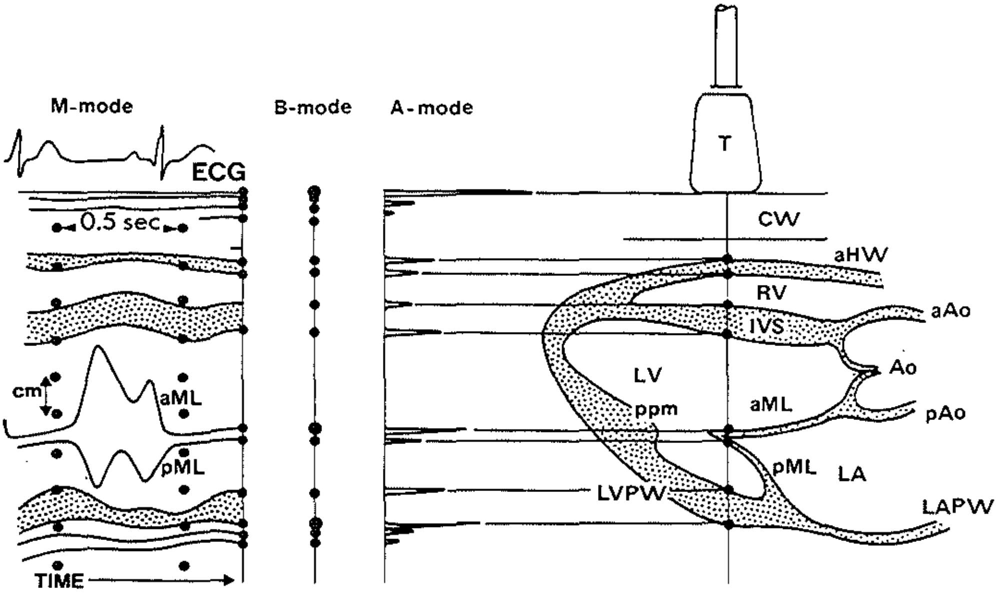

Figure 1.

Schematic cross-section of the heart from the base towards the apex with cardiac structures included. The single element transducer (T) in front is aimed so that the sound beam traverses from anterior to posterior; the chest wall (CW), the anterior heart wall (aHW), right ventricle (RV), interventricular septum (IVS), left ventricular cavity (LV), the tips of the mitral valve leaflets and the left ventricular posterior wall (LVPW). The echoes which originate from these boundaries are classically represented in three types of oscilloscope display and are referred to as the "A", "B" and "M-mode". For further explanation, see text.
Ao: aorta; aML: and pML: anterior and posterior mitral valve leaflets; LA: left atrium; LAPW: left atrial posterior wall; aAoW and pAoW: anterior and posterior aortic walls; ppm: posteromedial papillary muscle.

In the "A-mode", the height or amplitude of the echoes represents reflected energy from the boundaries. The distance of the boundary relative to the transducer is represented on the vertical axis (figure 1). Proper display of the signals requires the use of logarithmic amplifiers to compress the wide range of echo amplitudes and to match them to the display. Most instruments allow to control the gain as a function of time or depth (time gain compensation). Automatically adjusting time sensitive gain systems are now being introduced (5).

The "B-mode" is an intermediate step where the "A-mode" echoes are converted to dots and the brightness corresponds to the echo amplitude. The "B-mode" is well suited to produce a record of echo motion or "M-mode". This is realized by moving a recording surface such as photographic paper at a constant speed past the B-mode display. An electrocardiographic tracing is recorded simultaneously for timing purposes. Measurements are aided by centimeter depth markers which are displayed on the oscilloscope at calibrated time intervals of 0,5 second. The M-mode display permits recording of both the depth and motion pattern of intracardiac reflective surfaces relative to a fixed spatial reference and time. Time exposure or Polaroid photography allows to obtain good quality pictures of this information directly off the oscilloscope. However, the number of cycles recorded is limited and the pictures are small resulting in a large measurement error. Modern echocardiography utilizes fiberoptic strip chart recorders with high sensitivity and definition which allow echoes of cardiac structures to be recorded continuously on a handy paper strip and M-mode scanning to be performed (figures 2 and 3).

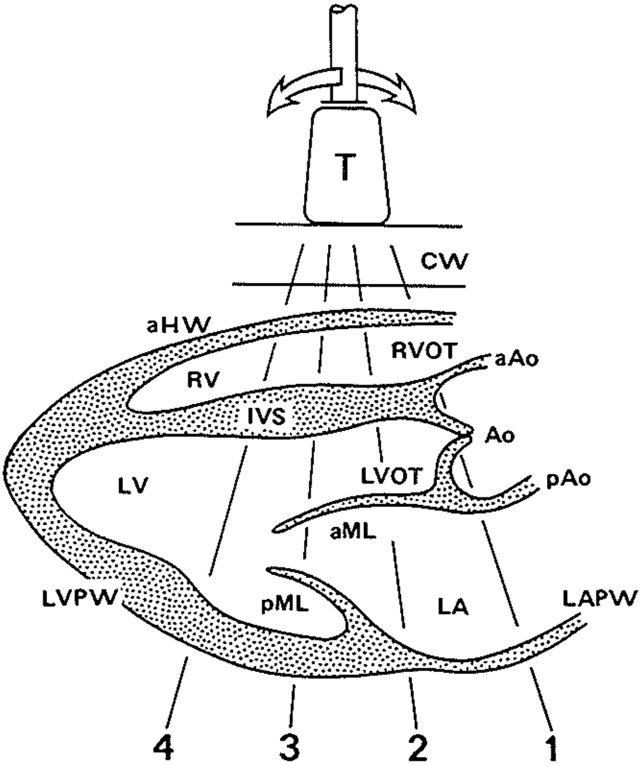

Figure 2.
Schematic cross section of the heart. A sector scan or M-scan is performed when the transducer is swept from the aorta (direction 1) towards the apex (direction 4). For abbreviations see figure 1.
RVOT and LVOT: right and left ventricular outflow tracts.

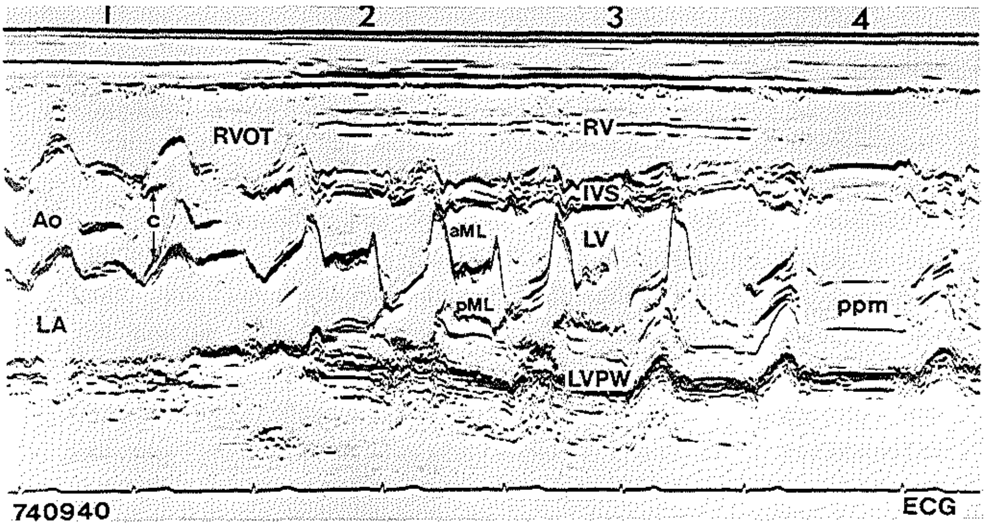

Figure 3.
M-mode scan of the heart following the sagittal plane through the long axis of the left ventricle. The directions of the sound beam labelled 1 to 4 on the diagram of figure 2, correspond to the areas labelled 1 to 4 on this record. For abbreviations see figure 1.
(from: Roelandt J.: Practical Echocardiology, Research Studies Press, Forest Grove, 1977).

Using the M-scan technique it is possible by sweeping the sound beam from one area of the heart to another while recording, to derive information concerning the spatial relationship of the structures examined.
This permits a more accurate identification of cardiac structures and in some conditions an anatomical diagnosis to be made. However, skill and experience to obtain these M-scans are required and the analysis is difficult as the resulting display is not simply related to the cardiac anatomy. The scans also vary with the speed and path of transducer movement and hence are qualitative at best. Indeed, the apparent lateral distances between the intracardiac structures on the M-scan recording reflect the

speed of transducer motion rather than the lateral anatomical dimensions. In addition the observed amplitude of motion is diminished by the angular relationship. Only the vectors of motion parallel to the sound beam are correctly displayed. As a result complex motion patterns are not accurately assessed. Furthermore, some distortion is also introduced as the cardiac cross-section scanned from a fixed point on the chest wall has a wedge shape which is represented in a rectangular format on the tracings. Yet, the method is accepted as a poweful diagnostic method for a variety of cardiac diseases (6, 7).

The continued need, however, for more quantitative spatial information concerning cardiac structure and function led to the development of real time two-dimensional imaging systems.

2.3 TWO-DIMENSIONAL ECHOCARDIOGRAPHY

The basic unit of information, the echo signal indicating the presence and the location in depth of a cardiac structure in the direction of the sound beam is the same for both M-mode and two-dimensional echocardiography. The principle of all these systems is that an acoustic beam scans a cardiac cross-section at a high rate in order to obtain instantaneous two-dimensional structure information and thus moving cardiac anatomy (see chapter 3).

The fundamental difference lies thus in the spatially oriented display which permits information to be appreciated and utilized which is meaningless in the absence of a spatial reference. This is illustrated in figure 4.

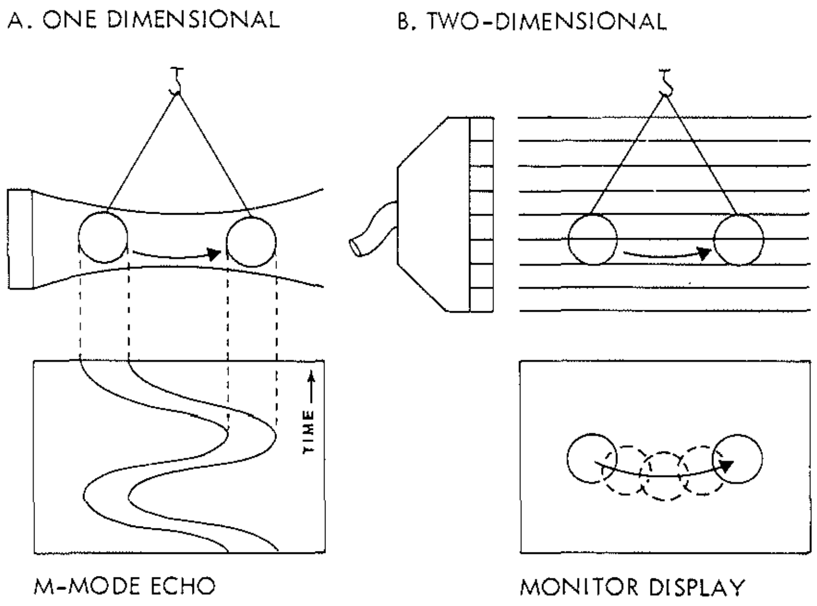

Figure 4.
Diagrams illustrating the difference in display of echo data between M-mode echocardiography (one-dimensional) and a two-dimensional echo system. A pendulum is considered as the target under study. The M-mode displays the distance from transducer to the target as a function of time. Thus, only the vector of motion of the pendulum parallel to the sound beam axis is recorded. No information about its shape is obtained. On the cross-sectional display, the shape of the target and its motion in all directions are recorded. A pendulum is readily recognized from the monitor display whereas it is not from the M-mode echocardiogram.

Let us suppose that the target of interest is a circular structure which swings in a plane following the sound beam axis of a single element transducer. The circular structure will be seen on the M-mode echocardiogram as parallel moving echoes. Their amplitude of motion only represents the vector of motion of the pendulum which is parallel to the sound beam axis. Both the shape of the target and the vectors of motion which are perpendicular to the sound beam axis are not recorded on the M-mode echocardiogram. With a two-dimensional imaging system, both the shape and the motion in all directions are identified and the pendulum is readily recognized from the monitor display. Thus, real time cardiac imaging provides both the pictorial image and a record of the motion of each echo signal. This allows identification of cardiac structures from both their anatomical relationships and specific motion patterns which is particularly helpful when studying unfamiliar cross-sections. Real time two-dimensional cardiac images relate closely to known, gross cardiac anatomy and look therefore more familiar to the cardiologist than M-mode echocardiograms. In addition, real time images yield an immediate visual feedback which allows the examiner to optimize gain setting controls and more importantly to adjust the transducer until the best cross-section is obtained.

2.4 RELATIVE ADVANTAGES OF M-MODE AND TWO-DIMENSIONAL ECHOCARDIOGRAPHY

Two-dimensional images are build up by many sound beams which scan the tomographic cardiac plane. This is time consuming and hence results in a limited frame rate in the order of 30 to 50 complete images per second. The resolution of motion of two-dimensional imaging systems is limited by this frame rate which is too low to record very rapid events like fluttering of valves, their opening and closing rates, etc. As a consequense, two-dimensional techniques are better able to visualize anatomic and structural rather than functional abnormalities.
The M-mode echocardiogram is sampled with a very high

repetition rate (1000 transmit receive cycles per second) and is therefore superior in demonstrating functional abnormalities (figure 5).

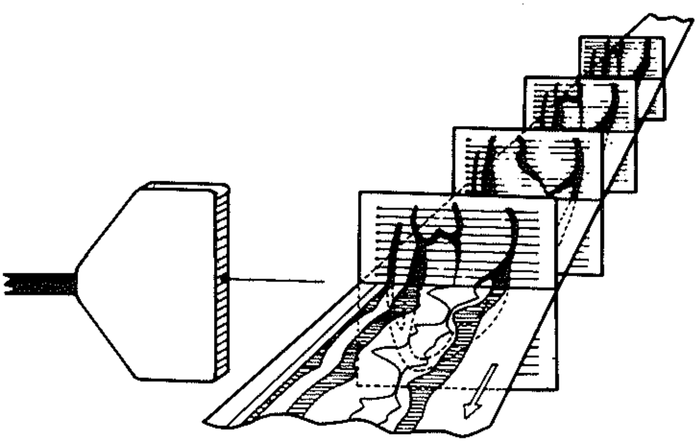

Figure 5.

Diagrammatic illustration of the relationship between a two-dimensional cardiac image and the M-mode display. The sampling rate of 1000 per second as used in M-mode echocardiography yields a clear definition of a small part of the mitral valve and an excellent resolution of its motion. However, this display gives little information on its anatomical relationships. This is present on the two-dimensional display. However the lower sampling rate of the two-dimensional images (30 to 50 per second) results in a lower resolution of motion.

Thus, it appears that both methods are complementary and mutually supportive in cardiac conditions where anatomic and functional abnormalities overlap.

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CHAPTER 3

ULTRASONIC TWO-DIMENSIONAL IMAGING SYSTEMS

Rapid advances have been made in cross-sectional ultrasonic imaging of the heart since its introduction in the late sixties. The early instruments never reached routine clinical application. It was the introduction of the linear array system at the Thoraxcenter in Rotterdam which in 1971 stimulated considerable interest in real time cross-sectional imaging of the heart. The enthusiasm of the clinicians who saw these images which looked like crude angiocardiograms generated a great deal of interest and investigation in the subject. In a few years, this system along with several others were developed into practical clinical tools.

3.1 EARLY DEVELOPMENTS

The ultrasono-tomograph described by Ebina et al (1), using a water bath B-scanner was able by rapidly angling the transducer, to produce real time images, in addition to compound B-scan images. A cinematographic technique, described in 1967 by Åsberg (2), used a reciprocating mirror system containing two reflectors and two transducers to obtain two-dimensional images at a rate of 7 frames per second. About the same time, Flaherty et al (3) developed an ultrasonic scanner which worked in conjunction with a fluoroscopic image to locate both the ultrasonic transducer and the cross-section being explored. With this instrument, sectors from 10 to 30 degrees at rates up to 40 frames per second could be obtained. Pätzold et al (4) used a sound source rotating in the focal area of a parabolic mirror so that parallel sound beams would produce a rectangular scan (Vidoson system). Images at a speed of 15 per second were obtained. Hertz and Lindstrom (5) also employed a water bath contact for their scanner. Fast sweeping of the sound beam across a cardiac cross-section resulted in images at a speed of 16 frames per second. Eggleton et al (6) originally devised a catheter with four small transducers at its top for intracardiac scanning. They modified this technique for intraoesophageal and later, precordial examination of the heart (7). Their experience obtained with these techniques finally resulted in the design of a mechanical hand-held sector scanner (7, 8). The practical clinical use of the earlier mechanical sector scanners (1, 3, 5) was limited by difficulties resulting from their complexity for routine application (large size transducers, water bath contact) and technical problems (gear wear, limited scanning rates).

3.2 CURRENT SYSTEMS

3.2.1 Mechanical sector scanners

Most technical problems were partially overcome with the introduction of the ultrasonocardiotomograph (9) and the hand-held mechanical sector scanners (8, 10, 11).
The latter are at present the simplest and consequently the least expensive of the real time ultrasonic scanners. The principle of image formation relies on the rapid pivoting motion about a fixed axis of a single transducer by means of an electrical motor contained within the transducer assembly (figure 1A). Signals from the transducer and an angle indicator are employed to generate video display. The resulting image is of a sector format. The frame rate is typically 30 frames per second with a field of view of 45 degrees. Larger fields of view are difficult to obtain because of skin contact problems at larger scan angles.
As an alternative to mechanical crankdriven pivoting systems, magnetic deflection or rotation mechanism (12) are also used to angle the transducer.
More recently, the spinning wheel mechanical scanners were introduced (figure 1B).

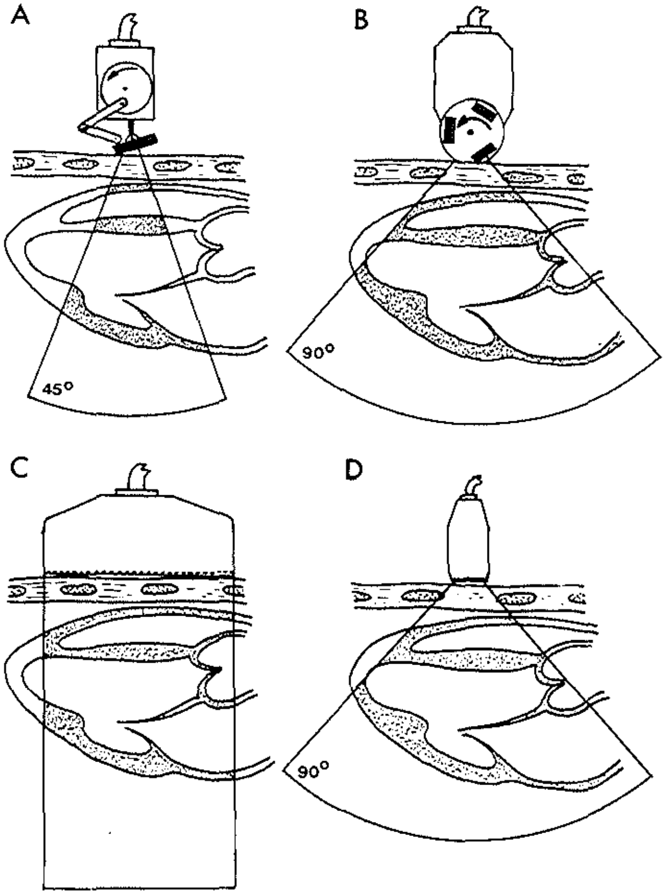

Figure 1.
Schematic representation of transducer designs from the four commonly used real time two-dimensional echocardiographic systems on the chest wall. The long axis cross-section of the left ventricle is visualized.

With three or four transducers on a rotating wheel it is possible to create sectorial beam deflection at a high repetition rate. Each transducer is active when it passes an acoustic window in the housing. A wider field of view of up to 90 degrees is obtained at a frame rate of 30

frames per second. The transducer is usually larger as compared to that of other real time scanners.
Advantages of the mechanical sector scanners is that they are easily adapted to existing M-mode units and that only a small acoustic window on the heart is required.

3.2.2 Linear array scanners

Meanwhile, at the Thoraxcenter in Rotterdam, Bom et al (13-15) developed the multi-element linear array scanner (multiscan). This instrument consists of a number of individual crystals arranged side by side in a single transducer assembly. Cross-sectional images are produced by sequentially transmitting on each of the array elements or overlapping subgroups of elements and by receiving the echo information with the same elements for each B-mode line in the final display. Rapid electronic switching allows cardiac scanning at a high frame rate (50 per second) in a rectangular image format (figure 1C). A movie showing real time cross-sectional images of the heart was produced with the first prototype in 1971 (figures 2 and 3).
The first clinical studies were published from 1973 on (16-20). This instrument undoubtedly stimulated most of the subsequent interest in dynamic cardiac imaging. Similar approaches for cardiac imaging have been used later by other investigators (21, 22). The principle and technical aspects of this linear array scanner are more extensively discussed in chapter 4.

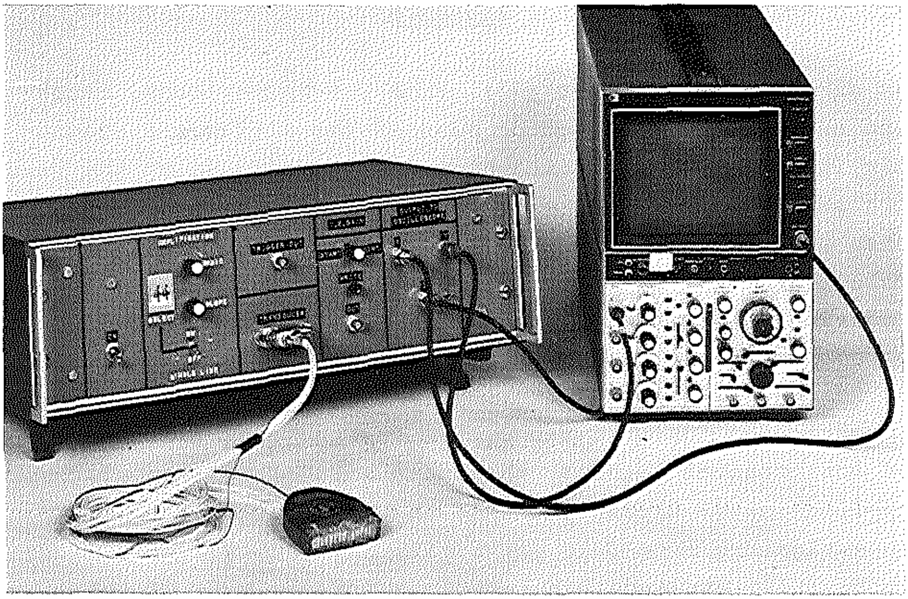

Figure 2.
Prototype of linear array scanner with which the first ultrasonic real time images from the heart were obtained in 1971.

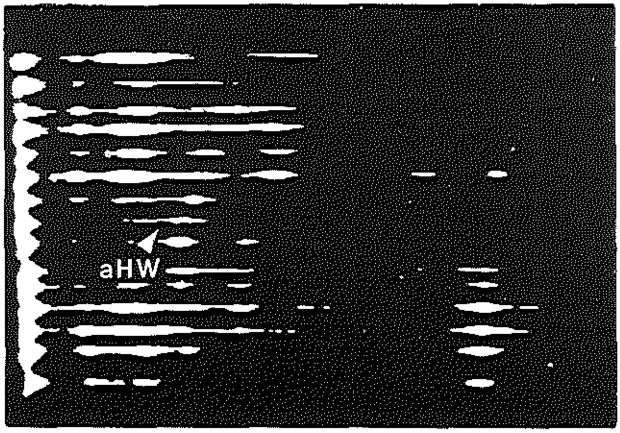

Figure 3.
First two-dimensional ultrasonic image obtained from a patient with severe pericardial effusion. The stop-frame representation does not readily allow structure identification. This was easier from the moving images. The anterior wall (aHW) is barely visible and is separated from the chest wall by the effusion. The poor sensitivity of the instrument did not allow the display of weak reflectors.

3.2.3 Phased array sector scanners

As early as 1968, Somer (23), from The Netherlands, reported on an electronic sector scanner for ultrasonic diagnosis (Electroscan). The scanning action produced by the transducer is based on electronic "beam steering" rather than electronic "beam stepping" as used in the multiscan. This means that by changing the firing sequence of the individual elements of the transducer, the sound beam can be swept through a cardiac sector up to 90° at a rate of 30 images per second (figure 1D). Unfortunately this investigator designed his system for the real time study of intracranial vessels, the brain being a more popular application of ultrasound than the heart at that time. Investigators from Duke University have subsequently succesfully applied this technique for analysis of the heart (Thaumascan) (24, 25). These type of scanners are the most complicated and, hence, the most costly. Advantages of these systems are their high resolution and the small transducer size allowing excellent maneuverability within the confinements of a small ultrasonic window.

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CHAPTER 4

THE MULTI-ELEMENT LINEAR ARRAY SCANNER (MULTISCAN)

Since the aim of this study is to describe the clinical implementation of the multiscan, it seems appropriate to briefly describe in this chapter the various aspects of this instrument which are pertinent to the clinician.

4.1 BASIC MULTISCAN PRINCIPLE

The early clinical instrument was based on the use of a linear array of 20 parallel single elements, packed in a transducer of 8 cm length and 1 cm width (figure 1).

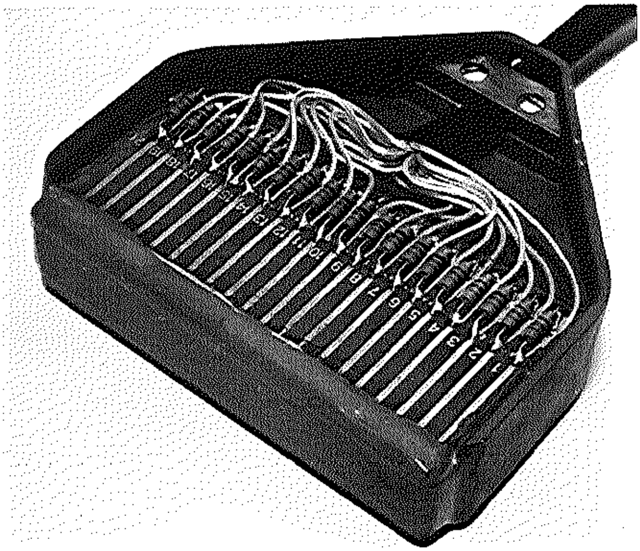

Figure 1. Multiscan transducer. It contains 20 elements and the active surface has a width of 1 cm and a length of 8 cm.

Beginning at the top of the transducer each single element (or a combination of elements) in sequence transmits a single sound beam into the tissues and receives echoes from the underlying acoustic boundaries. While the sound beam is scanned across the transducer probe, the image is

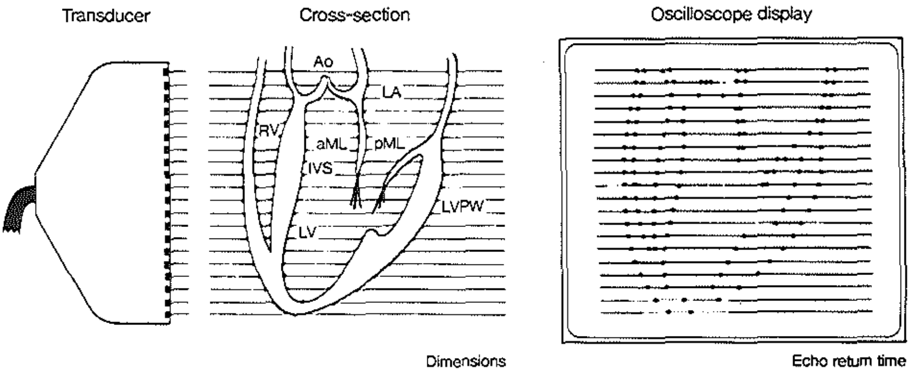

Figure 2.
Schematic representation of the sagittal left ventricular long axis cross-section with multi-element transducer placed in front and shown to the left. The drawing illustrates how ultrasonic images are created using this electronic scanning device. The crystals in sequence from top to bottom transmit an acoustic pulse into the tissues and subsequently switch into the reception mode. Received echoes from the acoustic boundaries (i.e. cardiac structures) are electronically converted to brightness dots (B-mode) and displayed along a horizontal line on the oscilloscope display. Echo positions on the display thus represent the cardiac dimensions in depth along that echo beam. On the vertical axis of the display, each echo line corresponds to the relative position of each crystal in the transducer. On the display, the outline of the cardiac cross-section is represented by brightness dots as indicated on the diagram. Fast electronic switching from one crystal to another results in real time visualization of the cross-section studied in its correct anatomic format. Abbreviations: Ao: aorta; aML and pML: anterior and posterior mitral valve leaflets; IVS: interventricular septum; LA: left atrium; LV and RV: left and right ventricle; LVPW: left ventricular posterior wall.
(Reproduced with permission from Roelandt and Bom (1)).

simultaneously created on the display oscilloscope screen and the horizontal lines are traced in positions corresponding to each beam arising from the transducer. The cardiac cross-section beneath the array of elements is visualized in real time by very fast electronic switching from one element to another (figure 2).

The cardiac cross-section visualized measures 8 cm (length of transducer) by 16 cm (determined by the transmit-receive cycle duration when the ultrasound velocity is approximately 1580 meter per second). Simultaneously with the cross-sectional images, patient identification symbols and the date of examination are displayed on top of the images. The electrocardiogram is at the bottom. Its right end edge indicates the timing of the cross-sectional image within the cardiac cycle. Actual cardiac cross-sections as obtained in 1973 are shown in figure 3A and B.

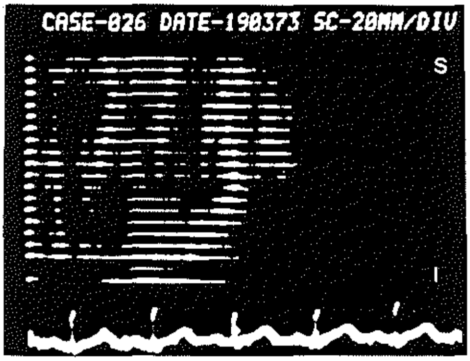

Figure 3A.
A long axis cardiac cross-section obtained from a normal subject with a 20 element linear array transducer in 1973. For orientation see figure 2. I: inferior; S: superior.

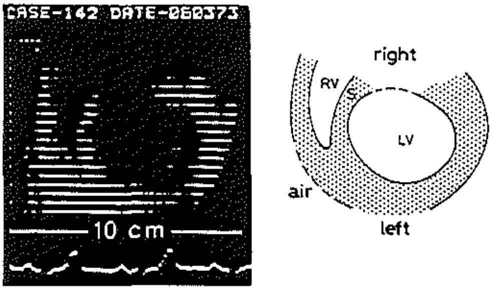

Figure 3B.
A short axis cross-sectional image obtained with the 20 element linear array transducer in 1973 from a normal subject. The left ventricular cavity appears as a circle. This examination is unique to ultrasound and is not available in real time in any radiographic technique. Abbreviations: LV: left ventricle; S: interventricular septum; RV: right ventricle.

4.2 RECORDING OF THE ULTRASONIC IMAGES

The rectangular image format is very suitable for direct conversion to video format. This allows the use of TV monitors for display and provides advantages for image recording since a video camera with inherent loss in image quality is not required. The conversion to video format is accomplished by a line converter which transforms the duration of each single echo data line (200 microseconds) to the standard video line duration (64 microseconds) (2). This is performed by storing the echo data temporarily into an electronic memory. At an appropriate moment in the video frame cycle, this memory is read out 5 times faster than the loading speed and the duration of the echo data line is so reduced from 200 to 40 microseconds. Thus, approximately two thirds of the TV screen width is used for display. The conversion is done for each echo data line, the patient identification characters and the electrocardiographic data. A frame counter adds a number to each frame (figure 4). This is helpfull for analysis and timing of events. At a frame rate of 50 per second the interval between two consecutive images is 20 milliseconds.

Digital processing of the basic echo information from adjacent crystals available from the line converter permits creation of additional interpolated display lines resulting in a higher line density per frame.

Standard video interlacing techniques eventually allow a further increase of the line density (figure 4).

"High line density" on the display should not be confused with "high acoustical resolution". This misconception probably originates from radiological methods where resolution is expressed in terms of the number of lines per inch that can be resolved on the X-ray picture. The difference and interrelationship between line density and acoustic resolution is diagrammatically represented in figure 5.

When a transducer consisting of 11 elements with a high acoustic resolution (i.e. narrow sound beams) is placed in

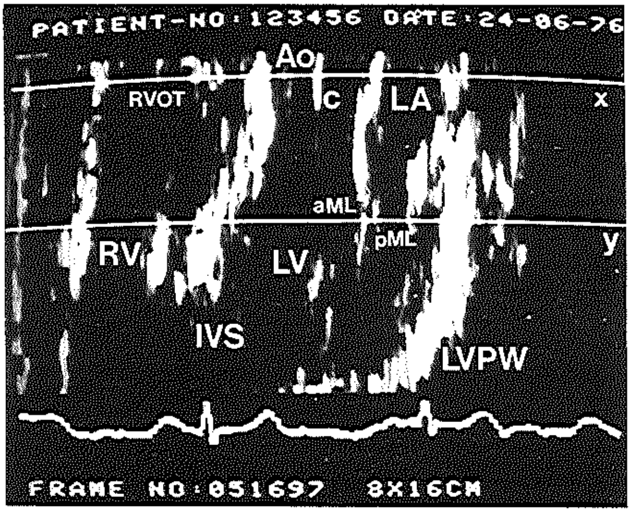

Figure 4. Sagittal left ventricular outflow tract or long axis cross-section obtained from a normal individual with a 20 element linear array scanner and a 320 line density display. For orientation, see diagram of figure 2. The horizontal lines x and y indicate two elements that are selected from the transducer for simultaneous or dual M-mode display. This facility permits the identification of the sound beam pathway, a more accurate analysis of motion patterns and measurement of time intervals between opening and closing of semilunar and atrioventricular valves (3).
Abbreviations: Ao: aorta; aML and pML: anterior and posterior mitral valve leaflets; IVS: interventricular septum; LA: left atrium; LV and RV: left and right ventricle; LVPW: left ventricular posterior wall; c: aortic valve; RVOT: right ventricular outflow tract.
(Reproduced with permission from Roelandt (4)).

front of two point reflectors "a" and "b" which are just in front of a crystal, both reflectors "a" and "b" will be displayed. In a high acoustic resolution-high line density system, the ideal "ultrasonic imaging" instrument, the picture would be as shown in the upper left panel. When half the number of crystals or a low line density display is used, only the reflector "a" will be seen (high acoustic resolution - low line density; lower left panel). However, with a low acoustic resolution or divergent beams, the situation changes. Crystals that are

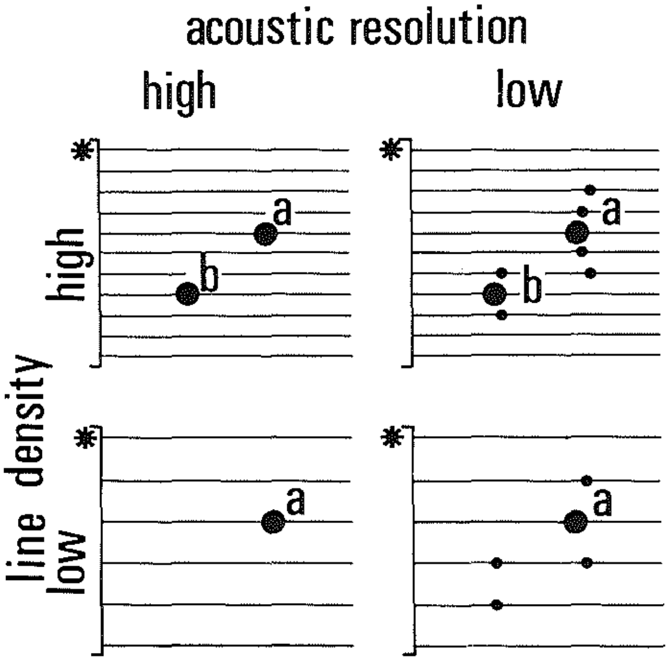

Figure 5.
Diagrammatic representation of the difference between line density on the display and acoustic resolution. For explanation, see text.

exactly positioned in front of a reflector will again correctly position the target echo on the display. Adjacent crystals however will, due to the beam spreading, also receive the target echo. As a consequence an erroneous echo display will occur. Following the same reasoning, reflector "b" will also be "seen" by the crystals at both sides and an echo will appear on their display axes as well (low line density - low acoustic resolution; lower right panel).

Increasing the number of display lines by interpolation will not result in an improved resolution but increase the number of "off-axis" echoes and accentuate the distortion (low acoustic resolution - high line density; upper right panel). These effects are applicable to cross-sectional images whether produced with a sector scanner or a linear array system. Nevertheless, the quality of the still frames obtained with a high line density is more visually pleasing although the ultrasonic information is basically not different.

4.3 THE RESOLUTION PROBLEM

The limitations of diagnostic ultrasound methods are caused by a variety of physical factors. These include the high dynamic range in echo amplitude and as a result difficulties in capturing all important information (e.g. weak reflectors may not be visualized).

The finite pulse length of the transmitted ultrasound energy is a major factor in determing the axial resolution. The axial resolving power of an instrument transmitting pulses 2 microseconds long is ± 1.5 mm. This is sufficient for diagnostic cardiac application.

By far the most serious limitation of cross-sectional imaging systems is their limited lateral resolution as a result of the finite sound beam width. The diverging beam causes spurious echoes on the display. These produce some distortion of structures and cavities since individual points on a structure are mapped into curved lines (figure 5 - upper right panel). These problems and their clinical importance are extensively discussed in chapter 10 and they deserve continued emphasis by the clinicion. The instrument resolutions published in the literature are difficult to compare because there is usually no indication of how, at what distance, at which gain settings and in what direction beam width measurements were made (5). The experienced echocardiographer, however, often makes a fairly reliable estimation of the resolving power of a particular instrument by viewing clinical results. Improving the lateral resolution of the imaging systems has been a major concern to all those involved in research and development of diagnostic ultrasound instruments.

4.4 DYNAMIC FOCUSSING

To improve the lateral resolution, dynamic focussing capabilities have been incorporated into the multiscan system (6). The linear array consists now of 51 smaller crystals of which sub-sets of 12 (n) elements are operating as phased arrays. This results in narrower parallel sound beams which scan the cardiac cross-section.
Each subsequent scan is performed with a new sub-set consisting of n-1 elements used for the previous scan and one new adjacent element. This enables one to realize 40 subsets of n elements and scans. Two focussing techniques are further employed (figure 6).

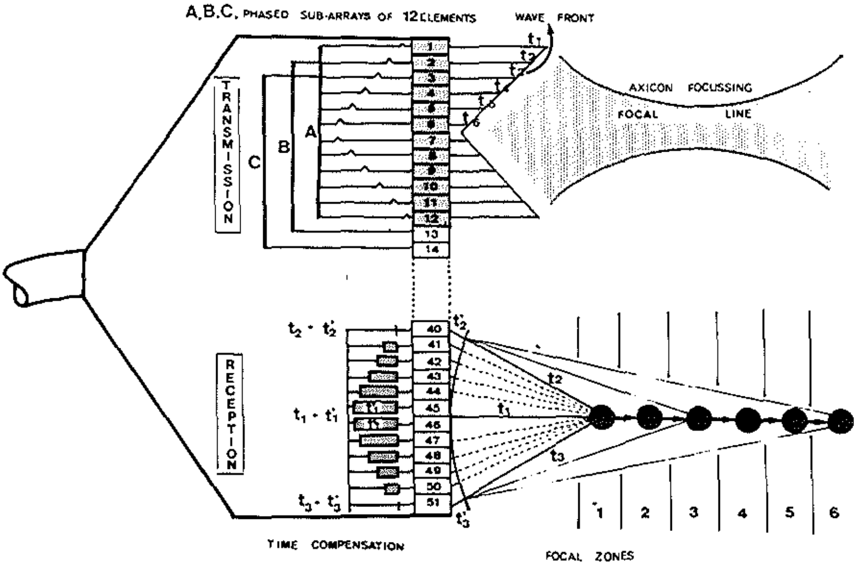

Figure 6.
Principle of dynamic focussing with a linear array transducer consisting of 51 elements. Sub-sets of 12 elements are used as phased arrays for both transmission and reception. The focussing principle during transmission is shown in the upper part and focussing during reception in the lower part of the diagram. For further explanation see text.

By firing the outer elements first and those to the middle progressively later with a very short time delay (t1-t2), an axicon focus is created in transmission (sub-set A of the upper part of the diagram).
The principle of focussing during the reception is indicated in the lower part of the diagram for the elements 40 to 51. The time during which echoes from a given depth area travel to the transducer is known and determined by the sound velocity. Echoes from a nearly reflector will arrive first. During this period, short delays in reception between the different elements are electronically introduced to cause the echo wave front to be in phase and hence to obtain a focussed image in the reflector area. The delays are sequentially adjusted for six depth zones. The same sequences are then repeated for all sub-sets of 12 elements used to create a complete cross-sectional image. The actual cardiac cross-section obtained with the dynamic focussed linear array consists of 40 display lines. Examples are shown in figure 7.

4.5 ANALYSIS OF TWO-DIMENSIONAL IMAGES

A significant problem for analysis of real time two-dimensional images forms the large amount of data that becomes available. The imaging rate of ultrasound real time systems is typically between 30 and 50 complete frames per second. This is much lower than the repetition rate used in M-mode echocardiography but dynamic structure information is now available in a spatially oriented format. The advantage is the capability to study dynamic cardiac anatomy but the enormous amount of data which results per unit of time creates difficulty for the analysis. To cope with this problem, and as a first practical step, the video processor is very useful since the moving images can be

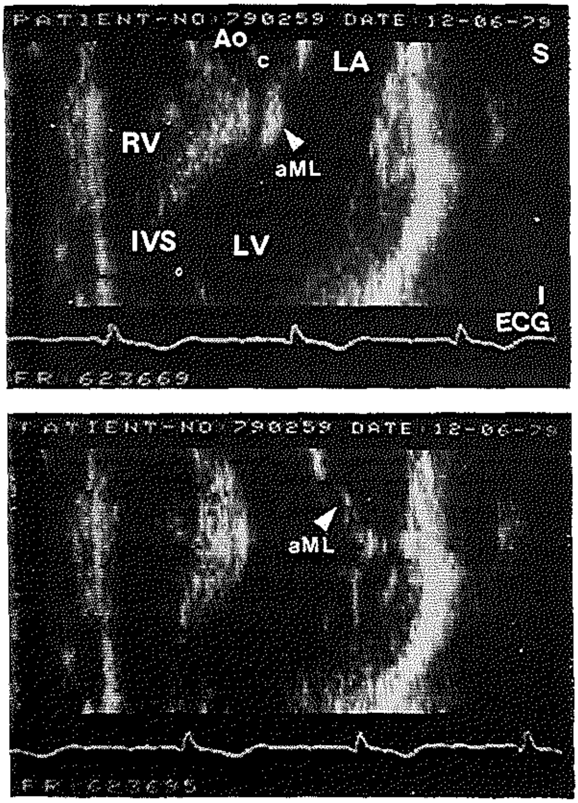

Figure 7.
Diastolic (upper frame) and systolic (lower frame) cross-sections obtained from a normal subject with the dynamic focussed linear array system. Note the anterior position of the anterior mitral valve leaflet (aML) in diastole and its closed position during systole.
Abbreviations:
Ao: aorta; c: aortic valve cusps; IVS: interventricular septum; LA: left atrium; LV and RV: left and right ventricle; I: inferior; S: superior.

directly recorded on video tape and analyzed later at actual speed, slow motion or still frame (2) (see under 4.2). Polaroid photographs for documentation can then be made from a slave TV monitor.
An additional facility of the instrument allows one to select any individual or two crystals simultaneously (dual M-mode) and to record the basic echo data from the B-mode on the two-dimensional images, in the M-mode (3). This principle is illustrated in figure 4 of this chapter and figure 5 of chapter 2.
It is exactly the same approach as employed in quanti-

tative angiocardiography where analysis of video lines is used rather than the complete images to track motion patterns of specific cardiac structures (7). The advantage of selecting individual crystals from the multiscan transducer is that the sound beam pathway through the cardiac structures is easily identified. This allows a more accurate measurement of motion and dimension of the structure under study. Alterations of these parameters which result from beam angulation (only the vector of motion along the sound beam axis which dimishes by the angular relationship is recorded) can be accounted for. However, this process of analysis is very time consuming and as yet not very practical. More recently, a recording system for direct storage of a time series of cross-sectional multiscan images in digital format has been developed (8). This will make rapid processing and advanced analysis of two-dimensional echo data possible in near future (9).

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CHAPTER 5

Multiscan echocardiography

Description of the system and initial results in 100 patients

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Summary

A multi-element ultrasound system has been developed to provide instantaneous two-dimensional cross-sectional images of the heart in motion. The system expands the capabilities of echocardiography by providing unique information regarding anatomic relationships and function. A systematic technique for clinical studies has been evolved and initial results in 100 patients indicate that records of satisfactory quality can be obtained in most patients. The multiscan system appears to be of considerable promise for non-invasive studies of the heart.

Samenvatting

Een nieuw ultrageluid systeem waarbij gebruik gemaakt wordt van meerdere akoestische elementen wordt beschreven. Hiermee is het mogelijk de bewegingen van het hart twee-dimensionaal weer te geven. Dit systeem verruimt de mogelijkheden van de echocardiografie omdat belangrijke anatomische en functionele informatie wordt verkregen. De onderzoekmethoden en klinische toepassingen worden besproken. De resultaten verkregen in 100 patiënten laten nu reeds toe te stellen dat het 'Multiscan' systeem een belangrijke aanwinst is in cardiologische diagnostiek.

Introduction

Since 1954 when Edler and Hertz[1] first applied pulsed reflected ultrasound as a method for cardiac examination, many studies have demonstrated its clinical usefulness[2,3,4]. Echocardiography is now established as a valuable non-invasive procedure for the assessment of many cardiac abnormalities. Despite this rapid advance as a diagnostic aid, there remain distinct limitations to the method, chiefly because thusfar single element transducers have been employed. These produce a 'flashlight beam' image rather than an 'overview' such as occurs with X rays. Aiming the probe requires skill and experience, and recognition of the origin of the echo is often difficult because the recorded image bears little resemblance to the anatomical boundaries of the heart. Furthermore, in the recent application of ultrasound to the analysis of ventricular dimensions and intracardiac volumes serious difficulties have been encountered because of the variations in ventricular geometry in cardiac diseases. There is also uncertainty as to the agreement between the echo axis of the left ventricle and the true anatomical minor axis. Several attempts have been made recently to obtain more reliable direct anatomical information[5-9]. However, these adaptions have been associated with additional problems such as bulky transducers, the necessity for triggering the exposure from the ECG, a limited scanning rate and a prolonged image assembly time. Consequently, a new approach not subject to these drawbacks has been sought for.

This study presents the data obtained in 100 consecutively studied patients from a new instrument of which an array of 20 fixed ultrasound elements forms the core. By means of fast electronic switching from one element to another, a real-time two-dimensional view of cross-sections of the moving heart is obtained.

Description of the system

The Multiscan 20** principle can be best described as the use in rapid succession of 20 parallel single elements with display from each element in the brightness mode (B-mode) at almost the same instant. The system has been described elsewhere by Bom et al [10,11].

The transducer. The transducer consists of 20 piezocrystals (figure 1). Each element measures 4 by 10 mm and the active area of the entire transducer is 80 by 10 mm. The number of 20 crystals on the line array of 8 cm is a compromise between the length of the cardiac cross-section to be viewed in adults, the desired manoeuvrability of the probe, the lateral resolution near the posterior wall and the line density on the display. The frequencies are the same as used in conventional echocardiography, 2.25 MHz. and 4.5 MHz. For optimal depth resolution a short acoustic pulse

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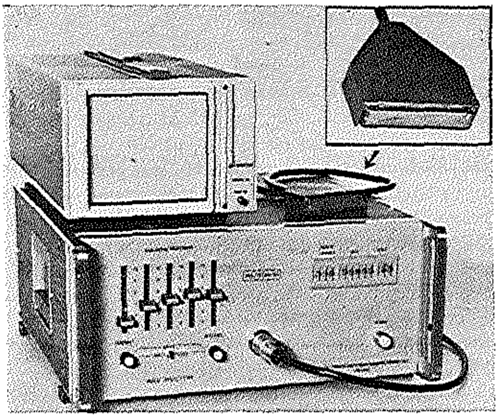


Figure 1 - Multiscan 20 cabinet and display monitor. The transducer is shown in the insert.

must be transmitted and therefore a 4 cm backing layer of tungsten (92%) and araldite (8%) was used. The inherent drop in sensitivity was compensated by means of a continuous wave excitation of ± 2 microsec. Selected depth penetration is 16 cm and the cross-section covered measures about 8 × 16 cm.

The apparatus and electronic circuitry. In working conditions, a sinusoidal current of short duration is fed into one single element of the transducer generating a short acoustic burst of approximately the same duration. Then, the element is switched in the reception mode for the next 200 microsec. The echo signals arriving at this element are amplified and fed into the processing part of the apparatus. This cycle is then repeated for each element in sequence by fast electronic switching, resulting in a repetition rate of 160 complete frames per second.

Propagated sound is in general always attenuated by spherical spreading and absorption. Reflectivity of the acoustic boundaries and the angle at which the ultrasonic beam hits this boundary will also influence the amount of reflected sound energy. To compensate for this, an independent time-sensitive gain correction is employed so that the depth gain be adjusted for an optimal display of specific portions of the cross-section. This consists of 5 levers, each selecting the amplification over a range of 80 dB at a different depth and independent of any of the other levers. The front panel is very simple, as shown in figure 1. In addition to the 5 depth control levers, an on-off switch, settings for patient identification data and controls for video processing are present. The dimensions of the Multiscan cabinet without displays are 42 × 45 × 17 cm and its weight is 15 kg.

Display and storage of the images. For each element, the video signal of the returning echoes is converted to intensity or brightness dots (B-mode) and displayed on the horizontal axis of the oscilloscope. On the vertical axis of the oscilloscope, the height corresponds to the relative position of each element in the transducer.

The patient identification symbols, the continuous electrocardiogram and the cross-sectional image are displayed simultaneously on the oscilloscope face.

For routine studies, all data are stored on magnetic videotape which allows playback for motion studies later. However, about 30% of the quality of the original image is lost in this process. For quantitative analysis of the data, other methods of image display are possible. The first utilizes 35 mm movie film recorded from the oscilloscope.

However, the camera speed is limited compared to the high frame repetition rate of the Multiscan and results in smearing of the echo dots. Single frame polaroid photographs from the oscilloscope screen have also been taken, but the size of the pictures is rather small for measurements. A third display method for quantitative analysis employs a line scan recorder connected directly to the Multiscan. Any line in the B-mode can be fed into the recorder and displayed in the M-mode. This facilitates measurements on selected lines of which the position through the cardiac cavities is known.

Calibration. Range calibration can easily be performed in the same way as with conventional echo systems, using a calibrated perspex block. Marks on the oscilloscope screen then allow easy adjustment to the proper 8 × 16 cm viewing area.

Resolution. The depth resolution depends largely on pulse wave length. The Multiscan pulse length of 2 microsec. is of the same order as presently available good quality single element systems. Lateral resolution depends on many factors such as the dynamic range of the system, selected gain settings and probe frequency. The lateral resolution of the Multiscan will be discussed extensively elsewhere[12].

Intensity level. Ultrasonic intensity is usually expressed as average intensity in watts per square centimer. The average acoustic intensity at 2.25 and 4.5 MHz. was measured in a water tank to be less than 2 milliwatts/cm^2 6 cm in front of the center of the transducer and is within known limits of safety[13].

Technique of examination

Efforts have been made in the first 100 patients to establish the most efficient examination procedure and to establish standard views for rapid recognition of the different cardiac structures and cavities.

Patient position. The patients were examined in the supine position with the head of the bed raised about 20° to 30°. A change in the position of the patient has occasionally, though not significantly, enhanced the images.

Transducer position. In the *oblique position* the transducer is placed to the left of the sternum with the upper end at the costo-sternal border. The lower end is angled laterally about 25° from the midline (figure 2A). This produces a sagittal cross-section through the heart in a plane from the base of the heart towards the apex (figure 2B). When the probe is pointed straight posteriorly, the aortic (Ao) root is the first structure identified. Slight tilting of the probe to the right or left establishes that position in which both the Ao root and the cusps are seen. In this position the left atrium (LA) is posterior and part of the right ventricular (RV) cavity and/or pulmonary outflow tract are anterior to the Ao. Also, the anterior leaflet of the mitral valve (aMVL) can be seen as it extends downward in direct continuity with the posterior Ao wall. The interventricular septum (IVS) is usually less clearly identified as the structure which extends directly

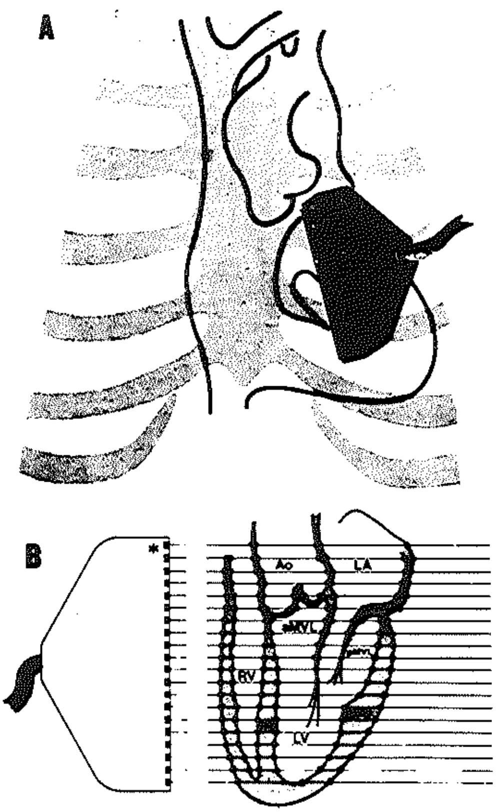


Figure 2 - A schematic drawing of the transducer in the oblique position to the sternum on the chest wall is shown on panel A. Panel B shows the cardiac structures lying in the plane under the transducer. (abbreviations: RV: right ventricle; IVS: interventricular septum; Ao: aorta; LA: left atrium; aMVL and pMVL: anterior and posterior mitral valve leaflet; LVPW: posterior left ventricular wall)

from the anterior Ao wall into an anterior direction. Improved definition of the wall of the left atrium (LA) and the posterior wall of the left ventricle (LVPW) can be obtained when the transducer is aimed to the patients left. When the probe is directed to the right of the patient, the IVS, RV cavity and pulmonary outflow tract will be better defined. Figure 2B shows diagrammatically the cross-section of the heart visualized with this transducer position and figure 4 shows systolic and diastolic frames taken with a polaroid camera from the oscilloscope screen. In the *horizontal position* the transducer is placed to the left of the sternum nearly perpendicular to the oblique position and approximately along the 3rd or 4th intercostal space. The upper end of the transducer is to the patients right and forms the top of the image on the oscilloscope (figure 3A). The resulting image is a cross-section through both the RV and LV at a ± 90° angle with the long axis of the heart. It is diagrammatically shown in figure 3B. The LV is posterior to the RV with the IVS at a slight angle from the upper right to the lower left. A tilt in superior direction establishes that position where the cross-section RV and LV is largest and where the IVS is best defined. The aMVL can always clearly be identified by its movement in the LV cavity. Directing the probe further superiorly shows the IVS merging into the anterior Ao wall and the aMVL into the posterior wall.

Limitations. The Multiscan is subject to the same physical limitations of sound transmission and reflection as conventional single element systems. The commonest cause of failure is a small pericardial window due to pulmonary emphysema or an ante-

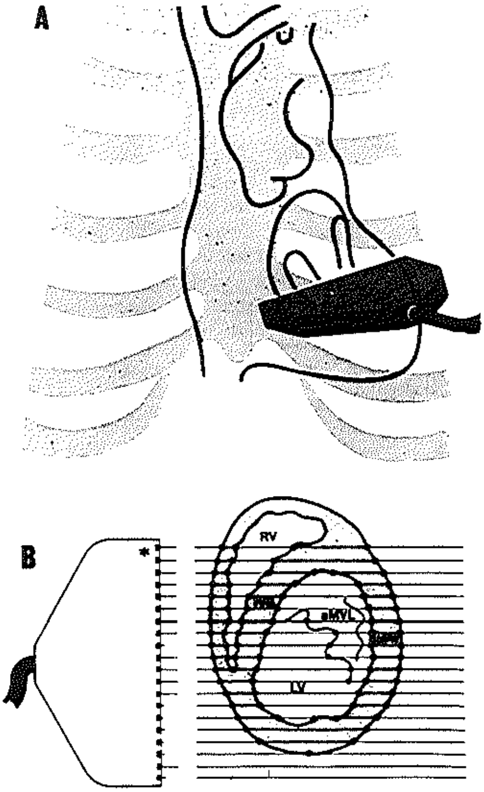
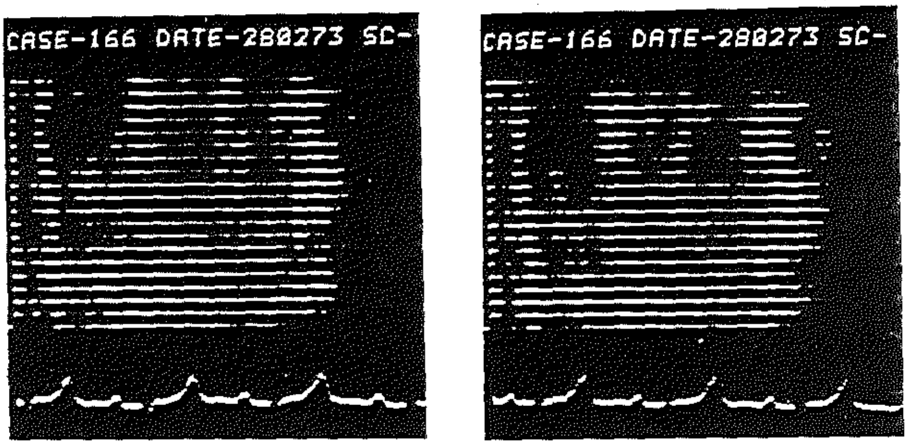


Figure 3 - The transducer in the horizontal probe position on the chest wall is shown in panel A. Panel B shows cardiac cross-section and structures included. (abbreviations: RV: right ventricle; IVS: interventricular septum; LV: left ventricle; aMVL: anterior mitral valve leaflet and LVPW: left ventricular posterior wall)



SYSTOLE **DIASTOLE**

Figure 4 - Systolic and diastolic frames photographed from the display oscilloscope using a polaroid camera. Orientation is as in figure 2B. The Ao root is seen in the upper center with the cusps visible in diastole. The IVS is in continuity with the anterior Ao wall and the aMVL with the posterior Ao wall. The aMVL is in the open position near the IVS in diastole and in a more posterior position when closed in systole. The right end of the ECG tracing indicates the position of the frame in the cardiac cycle. On top, the patient code number and date of study are visible.

rior chest wall deformation. Intervening dense tissue such as heavily calcified ribs may obscure strips of the image, especially in elderly people. However, considerable detail is still often visible between the obscured areas, much like looking at a chest X-ray. Distortion of images behind ribs because of higher ultrasound velocities in bone has not been observed. Difficult or unsatisfactory studies sometimes occur due to a large antero-posterior chest diameter with resulting greater depth of the structures to be studied.

Results

1. *Recognition of specific cardiac structures*

The frequency and quality with which specific cardiac structures were recognized in 100 patients are shown in figure 5. These patients were in all age groups representing a wide spectrum of cardiac disease. Quality of the images was graded subjectively from 1 to 5 as excellent, good, fair, poor or not seen. The dominant echoes or the Ao root are usually the best recognized structures during a Multiscan examination. The quality of the Ao root image was good or excellent in 75% of the cases. The Ao cusps were seen during diastole in most of the patients in whom a good Ao root picture was obtained. In a few patients the cusps were seen against the Ao wall during systole as well.

Good or excellent pictures of the aMVL were obtained in 67% of the cases. The pMVL was well defined (good or excellent in 54%). The anterior leaflet of the tricuspid valve was not seen in most cases. No consistent attempts were made to visualize the pulmonic valves. The IVS was seen with good or excellent detail in 58% of the cases; the left side was often better defined than the right side. The LVPW was usually clearly seen (good or excellent in 80%) but no attempt was made in this

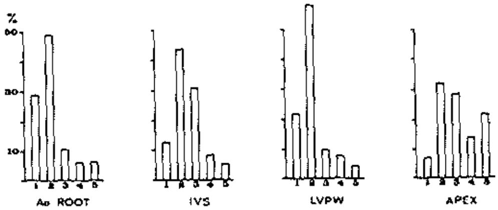


Figure 5 - Multiscan image quality in 100 patients. Structures were evaluated on the monitor display and graded excellent (1), good (2), fair (3), poor (4) or not seen (5).

The height of the bars gives the results in percent. (abbreviations: aMVL and pMVL: anterior and posterior mitral valve leaflet; aTVL: anterior tricuspid valve leaflet; AoC: aortic cusps; IVS: interventricular septum and LVPW: left ventricular posterior wall) study to differentiate the endocardium from the epicardium. In patients with smaller ventricles the apex was often clearly seen.

2. *Qualitative analysis: anatomy and motion*

The cross-section of the heart obtained by the Multiscan with the probe in the oblique position is the same as the plane through which the single element is rocked performing the standard M-mode sweep from the apex towards the base of the heart. The anterior and posterior aortic walls present as two parallel echoes which move anteriorly during systole and posteriorly during diastole. The sinuses of Valsalva narrowing into the aorta can usually be outlined. The cusps are seen centered in the Ao root in diastole and in excellent studies can be followed during opening and in systole as well. Immobile and calcified cusps in cases with aortic stenosis are seen as dense fixed echoes.

The aMVL is a direct continuation of the posterior Ao wall and terminates in the region of the posterior papillary muscle. The aMVL is usually best seen with the probe in the vertical position and appears as a thin, freely moving structure which travels anteriorly in early diastole, partially closes, then re-opens during atrial contraction. The M-shaped motion pattern known from single element studies can be recognized from this. It is difficult to define the free edge of the aMVL as it often appears as a continuous structure from the posterior Ao wall to the posterior papillary muscle, including the chordae. The pMVL appears much shorter and less mobile and moves in the opposite direction as the aMVL in diastole.

In mitral stenosis, aMVL motion becomes jerky and stiff with decreased amplitude, and the valve apparatus as a whole seems to bulge anteriorly in diastole. With severe mitral stenosis the aMVL becomes fixed. Occasionally, one could see the pMVL moving in the same direction with the aMVL in diastole instead of in the opposite direction, as occurs normally.

Fibrosis and calcification of the valves are indicated by a dense and/or a thickened echo. In cases of prolapsing mitral valve syndrome, a flailing exaggeration of the normal diastolic movement and occasionally the aMVL prolapsing past the pMVL was seen in systole.

The LV epicardium and pericardium are the best reflectors for ultrasound of the heart and the LVPW is clearly delineated posteriorly by these echoes. Anterior to these are multiple echoes seen which represent myocardium and endocardium. In good studies, the higher amplitude of motion of the endocardial echo in relation to the epicardial echo was striking. This was also demonstrated by recording the echoes of each line of the Multiscan in time-motion on the line scan recorder. The cavity of the RV and the pulmonary outflow tract are only well delineated when RV hypertrophy or dilation is present.

The RV cavity in normals is often filled with echoes, perhaps because of the high degree of trabeculation, and definition of the endocardial surfaces is difficult with the transducer in the oblique position. In the horizontal position the RV cavity was more frequently well circumscribed. Most apparent however was the pivoting motion around a point in its middle of the IVS in RV overload conditions. In these patients an exaggerated up and down movement of the pulmonary outflow tract was consistently seen.

3. *Quantitative analysis: dimensional measurements*

In the first 100 patients an attempt was made to evolve a relatively standard technique for probe positioning, an efficient examination procedure and standard views for anatomic interpretation. No systematic attempts for quantitation and dimensional measurements were made. Definition of the anterior and posterior Ao wall is of sufficient quality that accurate measurements of the Ao diameter are possible. The LA cavity is usually well delineated and its diameter can be compared to that of the aortic root using the oblique transducer position. In mitral stenosis, the LA diameter is considerably higher than the Ao diameter.

When the IVS and LVPW are displayed simultaneously, dimensional analysis of the LV can be performed. On records from the line scan recorder using a selected single line passing through the LV cavity, good definition of the left side of the IVS and the posterior LV endocardium are often obtained. In patients where the apex is visible, the major axis of the LV can be measured, and in optimal records outlining the entire ventricle is possible, allowing LV volume calculations using the angiocardiographic formula[14]. When the apex is lacking it is still possible to select the most representative diameter of the ventricle and calculate the rate of midwall circumferential fiber shortening[15] and volume data using previously proposed echocardiographic formulas[16,17]. RV dimensional measurements will probably be possible only in patients with RV dilation and hypertrophy. The possibilities for analysis of ventricular images obtained with horizontal transducer position are still being assessed.

Comments

Echocardiography is a unique non-invasive procedure and yields important diagnostic information in many cardiac conditions[2,3,4]. However, with use of a single element in the M-mode, only a selected narrow portion of the heart in depth is studied as a function of time. This representation gives no information about adjacent cardiac structures and their anatomical relationships nor about activity of the heart as a whole. For these reasons, attempts have been made to solve these limitations and to obtain images of the heart in their real anatomic relationships[5-9].

The Multiscan system overcomes the limitations inherent in the single element technique as well as problems encountered with the other multidimensional systems, and provides instantaneous two-dimensional moving cross-sections of the heart.

Important anatomic and functional information about the heart can be obtained with the Multiscan. The anatomic relationships of different cardiac structures are visualized without distortion. This facilitates the overall orientation and recognition of echoes from specific structures. It also permits precise localization of structures, and its use in congenital heart diseases is a promising application. Qualitative motion analysis of specific cardiac structures such as the valves and ventricular walls is immediately available and offers many advantages and potential possibilities for evaluation of patients with valvular and coronary heart disease. The system allows quantitative measures of ventricular dimensions and derived volumes, since one knows the precise location of each echo axis through the LV.

The concept thus has a considerable potential in the non-invasive study of the heart. However, the present display methods are in their infancy and their potential cannot be fully assessed at this time. Technical improvements in the quality image display will perhaps expand further the possibilities of the system.

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CHAPTER 6

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Multidimensional echocardiography
An appraisal of its clinical usefulness

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Multiscan is a new concept in echocardiography providing instantaneous cross-sections of the heart in motion without distortion. The examination technique and the present display and recording methods are described and discussed in some detail.

Multiscan provides important anatomical and functional information in the non-invasive diagnosis of congenital malformations and of valvular heart disease. The size, shape, and overall function of the left ventricle can be assessed.

Localized disorders of wall motion are also detected, making the instrument useful for the study and follow-up of patients with coronary artery disease.

Quantitative measurements of cardiac dimensions and calculation of left ventricular volumes using the area-length method can be obtained. From the results presented in this paper one may conclude that the concept of Multi-element echocardiography is a valuable extension of the now widely accepted single element technique and offers vast possibilities for the screening, study, and follow-up of patients with cardiac disease.

Echocardiography is now established as a unique non-invasive diagnostic aid for many congenital and acquired cardiac diseases (Gramiak and Shah, 1971; Feigenbaum, 1972; Meyer and Kaplan, 1973; Popp and Harrison, 1973). However, in most studies where single element probes are used, only a selected, narrow, portion of the heart is explored in depth and recorded as a function of time (time-motion or M-mode). Therefore, no direct information about the anatomical relations of specific cardiac structures or about the activity of the heart as a whole is available. Yet, the importance of and the need for a multidimensional echographic display of cardiac structures has been demonstrated by the many attempts over the last few years to visualize the entire cardiac configuration with its true anatomical relations (Äsberg, 1967; Ebina *et al.*, 1967; King, 1973; Kikuchi and Okuyama, 1970; Hertz and Lündström, 1972; Gramiak, Waag, and Simon, 1972). Such a cross-sectional image should afford great advantages in the study of patients with valvular and congenital malformations. In addition, it would allow determination of the ventricular volumes and wall motion. Techniques described so far, however, produce 'frozen' images of the heart (Ebina *et al.*, 1967; King, 1973; Kikuchi and Okuyama, 1970) or have limited frame rates (Äsberg, 1967; Hertz and Lündström, 1972; Gramiak *et al.*, 1972). In fact, real time information about the dynamic function of the heart cannot be obtained with these techniques.

The present study provides the first clinical evaluation of a system with which two-dimensional cross-sections of the heart were recorded in real time with good resolution at 80 frames a second. Cardiac structures are visualized in their true anatomical relations and important functional information is obtained. In this paper, the examination techniques and the clinical applications of the system will be described in more detail.

Methods

The technical aspects of the multiple element echo system[1] have been described in detail in previous papers (Bom *et al.*, 1971, 1973a; Bom, 1972; Roelandt *et al.*; 1973). The core of the system consists of an 8 cm linear array of 20 fixed ultrasound elements. From each element,

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[1] ECHOcardioVISOR 01, Organon Teknika, Oss, The Netherlands.

the video signal of the returning echoes is converted to intensity or brightness dots (B-mode) and displayed on the horizontal axis of the oscilloscope. The anterior chest wall is always to the left on the display. The location of the signal from each element on the vertical axis of the oscilloscope corresponds to the position of the element in the transducer. Rapid electronic scanning of all elements and appropriate display of the echoes results in the instantaneous display of moving structures. Presently a 40 line oscilloscope image is produced by an 'interlacing' technique (alternating shift of 2 mm of the image) to provide a more pleasing image. This reduces the effective frame rate to 80 frames a second or half the original repetition rate. Patient identification symbols, the continuous electrocardiogram, and the cross-sectional image are displayed simultaneously on the oscilloscope face. By means of display of the electrocardiogram of the three preceding seconds at the bottom of each frame, the exact correlation with the cardiac cycle is achieved.

Depth calibration can easily be performed in the same way as with conventional echo systems using a calibrated perspex block. Markings on the oscilloscope screen allow adjustment to the approximate 8 × 16 cm viewing area. For the figures shown in this paper, a correction factor can be calculated, as the height of a frame always corresponds to 8 cm in the original recordings. The energy levels of the ultrasound in the system were measured in a water tank. Ultrasonic intensity is usually expressed as average intensity in watts per cm^2; the average acoustic intensity was found to be 0·6 mwatts/cm^2 at 2·25 MHz. At 4·5 MHz it was 2 mwatts/cm^2. Both were measured 6 cm in front of the centre of the transducer in a water tank. Peak intensity was measured to be 0·7 watts/cm^2 and 3·6 watts/cm^2, respectively. These intensities are well within recognized limits of safety (Woodward, Pond, and Warwick, 1970; Ulrich, 1971).

Recording techniques

While the best images are those directly available on the oscilloscope display at the time of study, permanent records are required for subsequent analysis. However, production of a 'hard copy' of the same quality as the original study poses serious problems. In our laboratory, several recording methods are used and have been assessed for specific applications.

Magnetic videotape

For routine studies, all data are stored on magnetic videotape which allows playback for motion studies later. It was found that about 30 per cent of the quality of the original image is lost in the process. This is chiefly because of the rather slow frame speed of the video system as compared to the multiscan frame rate and the time-constant and limited sensitivity of the video camera. Motion, however, is preserved though the details of finer structures, such as valve cusps, may be lost.

Cinematographic film

The original oscilloscope image can be recorded on 16 mm and 35 mm cine film. However, since the camera speed is less than the frame rate of the multiscan, the echo dots are superimposed on one film frame. This results in smearing. Increasing the film speed to 80 frames per second creates problems with film exposure time and synchronization. The quality of the images is good when viewed in motion but the quality of each individual frame is poor. However, interpretation and qualitative assessment of left ventricular dynamics is quite possible with the cine film recordings.

Polaroid photographs

Single frame photographs can be made from the oscilloscope screen by Polaroid camera. Their quality is reasonably good for quantitative measurements. Triggering from the QRS complex allows the recording of frames at selected moments in the cardiac cycle, such as end-systole and end-diastole. Polaroids are presently used for outlining the left ventricle and calculation of volumes. Furthermore, they are quite suitable for documentation of specific anatomical abnormalities but, with this recording technique, motion is not preserved. Most of the figures included in this paper are Polaroid photographs.

Individual element recording

The signal from any selected element of the multiscan transducer can be recorded on the line scan recorder[1] in the M-mode. This combines the two-dimensional orientation facility of the multiscan with single element recording and facilitates measurements on selected lines of which the position through cardiac structures is known. The resolution and definition of specific echoes is comparable to conventional single element M-mode recordings.

Line scan records

Complete frames can be recorded on the line scan recorder.[1] The format of these images is small (19 × 40 mm), being limited by the recorder paper speed. An increase in size of the images by a factor of 2 would call for increase of recorder paper speed from 500 to 1000 mm/sec in order to keep the cross-sectional geometry correct. However, definition of the echoes is good and this recording technique is most promising. These 'postage stamp size' pictures are recorded at 25 frames a second simultaneously with the electrocardiogram.

Examination technique

Position of patient

Patients are examined in the supine position, with the head of the bed raised about 20° to 30°. A change in the position of the patient occasionally enhances the images. In our experience, turning the patient slightly on his left side allows better visualization of the interventricular septum and left ventricular posterior wall simultaneously. This is especially important for dimensional measurements and the outline of the left ventricle for the calculation of left ventricular volumes.

[1] Honeywell 1856 Visicorder.

Transducer positions

The transducer can either be held in a fixed position on the chest or a scanning movement can be performed. It is clear that the exact position and direction of the probe will differ from patient to patient and the described technique is only applicable when no significant changes in the configuration or position of the heart are present. A routine multielement echographic examination should always consist of displaying the long-axis cross-section first, followed by a transverse cross-section through the left ventricular cavity and a transverse scan.

Long-axis or oblique position In this position, the transducer is placed obliquely to the left of the sternum with the upper end at the costosternal border. The lower end is angulated laterally about 25° from the midline. This produces a cross-section through the long axis of the heart in a sagittal plane from the base of the heart toward the apex (Roelandt *et al.*, 1973; Kloster *et al.*, 1973a). When the probe is pointed straight posteriorly, the aortic root is the first structure identified in the upper part of the screen. Slight tilting of the probe to the right or left establishes that position in which both the aortic root and the cusps are seen. In this position the left atrium is posterior and part of the right ventricular cavity and/or pulmonary outflow tract are anterior to the aorta. The anterior leaflet of the mitral valve can be seen as it extends downward in direct continuity with the posterior aortic wall (mitral-aortic continuity). The interventricular septum is usually less clearly identified as the structure which extends directly from the anterior aortic wall (septal-aortic continuity) into an anterior direction. Improved definition of the wall of the left atrium and the posterior wall of the left ventricle can be obtained when the transducer is aimed to the patient's left. When the probe is slightly directed to the right of the patient, the interventricular septum, right ventricular cavity, and pulmonary outflow tract can be better seen.

Transverse position and scan In the transverse position the transducer is placed to the left of the sternum perpendicular to the long-axis position and approximately along the 3rd or 4th intercostal space. The upper end of the transducer is to the patient's right and forms the top of the image on the oscilloscope. The resulting image is a transverse cross-section through both the right and left ventricle at a ±90° angle with the long axis of the heart (Roelandt *et al.*, 1973; Kloster *et al.*, 1973a). The left ventricle is posterior to the right ventricle with the interventricular septum at a slight angle from the upper right to the lower left. By tilting the transducer in a superior or an inferior direction, a two-dimensional transverse scan of the heart along the long axis can be performed (Fig. 1). A tilt in a superior direction establishes that position where the cross-sections of the right and left ventricles are largest and where the interventricular septum is best defined (Fig. 2A). The anterior leaflet of the mitral valve can be identified by its movement in the left ventricular cavity. Directing the probe slowly superiorly shows the interventricular septum merging into the anterior aortic wall (septal-aortic continuity) and the anterior leaflet of the mitral valve into the posterior aortic wall (mitral-aortic continuity). In the transverse cross-section when the base of the aorta is seen, the left atrium is sometimes clearly outlined posterior to the aorta (Fig. 2B). During this scan, the anterior tricupsid valve often becomes visible in the cross-section just below the aorta. In infants, where calcified structures in the anterior chest give no impediment to sound transmission, it is actually possible to displace the transducer stepwise from the apex towards the base and the great vessels, resulting in successive parallel cross-sections. The transverse scan and/or stepwise displacement of the transducer is very important for the diagnosis of congenital malformations, as cross-sectional anatomy can be assessed without any distortion.

Results

Up to the time of writing, 296 patients have been studied with the system. In the first 100 patients,

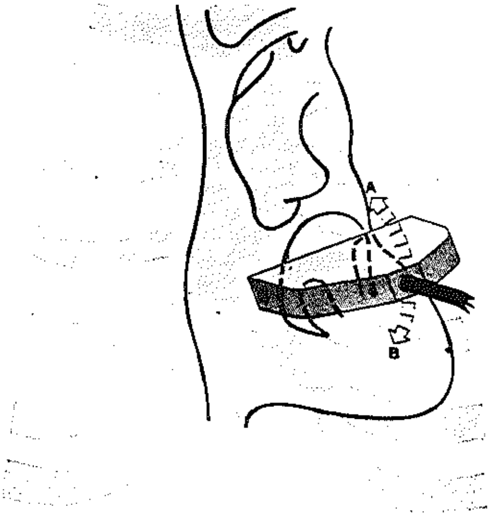

FIG. 1 *A schematic drawing of the transducer in the transverse position on the chest. The upper end of the transducer is to the patient's right and is the top of the cross-section displayed on the oscilloscope. By tilting the transducer a two-dimensional transverse scan along the long axis of the left ventricle is performed. The resulting image in position A is a transverse cross-section through both the right and left ventricle. In position B, the root of the aorta is visualized with the right ventricular outflow tract anterior and the left atrium posterior to it (see Fig. 2). During this scan a large part of the left ventricle can be studied and the septal-aortic and mitral-aortic continuity can be examined.*

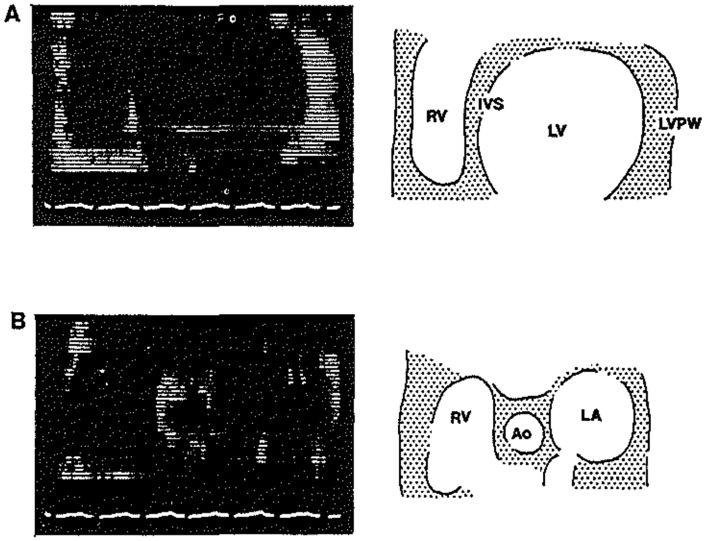

FIG. 2 *Two transverse cross-sections are shown with the transducer in positions A and B as shown in Fig. 1. The anterior chest wall is to the left. The resulting cross-section in position A is seen in panel A. The left ventricle (LV) is posterior to the right ventricle (RV) with the interventricular septum (IVS) at a slight angle from the upper right to the lower left. (LVPW = left ventricular posterior wall.) The lower cross-section is obtained with the transducer in position B (Fig. 1). The root of the aorta (Ao) is clearly delineated with the left atrium (LA) posterior and part of the right ventricle (RV) anterior to it. The cross-sections were obtained in a patient with cardiomyopathy. The size of the left ventricle is enlarged and there is also left atrial enlargement due to mitral incompetence.*

efforts were directed to develop the most efficient examination technique and to establish standard views for rapid recognition of the different cardiac structures and cavities, as described above. Clinical evaluation forms were used to determine the capabilities of the system, including the overall quality of the study, the frequency and quality of recognition of specific structures, and the possibility of making a clinical diagnosis from the oscilloscope display. The results are described in detail elsewhere (Roelandt *et al.*, 1973; Kloster *et al.*, 1973a; Bom *et al.*, 1973b). In brief, good or excellent studies with satisfactory recognition of the mitral and aortic valves and left ventricular walls were possible in over two-thirds of all adults and in nearly all infants and children. Specific cardiac diagnoses could be made in about 40 per cent of patients.

Applications of system in diagnostic cardiology

Normal cardiac cross-sections The cross-section of the heart obtained by the multiscan with the probe in the oblique position is the same as that plane through which the single element is rocked when one performs a sector scan from the apex towards the base of the heart (Feigenbaum, 1972). However, these structures are now visualized two-dimensionally in their true anatomical relations and in real time motion. Such a cross-section is shown in Fig. 3 in diastole and systole. The anterior and posterior aortic walls present as two parallel echoes which move anteriorly during systole and posteriorly during diastole. The sinuses of Valsalva can usually be outlined and the cusps are seen centred in the aortic root in diastole. In the best studies they can be followed during opening and throughout systole as well. As the left atrium is posterior to the aorta and its dimension normally never exceeds that of the aorta, confusion with this structure is impossible. The anterior leaflet of mitral valve is a direct continuation of the posterior aortic wall (mitral-aortic continuity) and terminates in the region of the posterior papillary muscle. Therefore, the anterior leaflet of the mitral valve is usually best seen with the probe in the long axis position. It

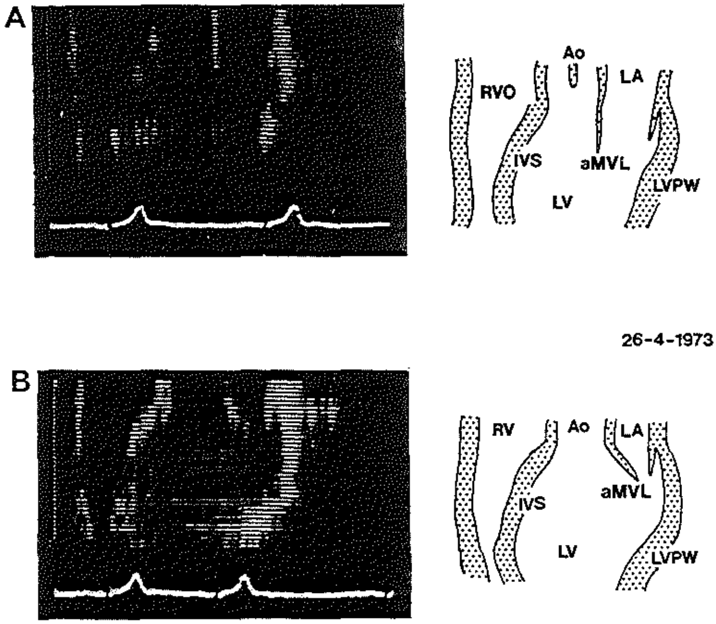

FIG. 3 *End-diastolic (A) and early systolic (B) long-axis cross-sections are shown. For orientation see diagrams. The aortic root (Ao) is seen in the upper centre with the cusps visible in diastole. The right ventricular outflow tract (RVO) is anterior to the aorta and the left atrium (LA) posterior to it. The interventricular septum (IVS) is in continuity with the anterior aortic wall (septal-aortic continuity) and the anterior mitral valve leaflet (aMVL) with the posterior aortic wall (mitral-aortic continuity). The anterior mitral valve (aMVL) in diastole is in an open anterior position and in a posterior and superior position when closed in systole. The right end of the electrocardiographic tracing indicates the position of the cross-section in the cardiac cycle. (LV = left ventricle; LVPW = left ventricular posterior wall.)*

appears as a thin, freely moving structure which travels anteriorly in early diastole, closes partially, then reopens during atrial contraction. During systole, closure of the mitral valve takes place primarily by a posterior and superior movement of the anterior leaflet of the mitral valve against the posterior leaflet. It is difficult to define the free edge of the anterior leaflet as it often appears as a continuous structure from the posterior aortic wall to the posterior papillary muscle, including the chordae. The motion of the posterior leaflet of the mitral valve varies between individuals, but is always much shorter, less mobile, and moves in the opposite direction from the anterior leaflet in diastole. The interventricular septum is in continuity with the anterior aortic wall (septal-aortic continuity). In general, the left side of the interventricular septum is clearly seen whereas the right side may only be definable when some right ventricular enlargement is present. The left ventricular epicardium and pericardium are the best reflectors for ultrasound of the heart and the left ventricular posterior wall is clearly delineated posteriorly by these echoes. Anterior to these, multiple echoes are seen which represent myocardium and endocardium. This was verified by recording the echoes of each line of the multiscan in time-motion on the line scan recorder.

The cavity of the right ventricle and the pulmonary outflow tract are only well delineated when right ventricular hypertrophy or dilatation is present. Of great importance is the study of the movement of the left ventricular wall. The long-axis cross-section closely resembles the outline of the left ventricular cavity as seen on the left ventricular angiograms in the right anterior oblique position. Therefore, it is possible to analyse the contraction


END-DIASTOLE


END-SYSTOLE

FIG. 4 *Transverse cross-sections in end-diastole and end-systole in a normal individual are shown. The left ventricular cavity is clearly outlined. Motion of the ventricular walls in this cross-section was symmetrical and this could easily be assessed on the oscilloscope display.*

pattern and motion of the septum and posterior left ventricular walls. Furthermore, with the transverse scan, the contraction of the left ventricular myocardium can be studied in different cross-sections and a greater percentage of the left ventricle is accessible for wall motion analysis than with conventional angiographic techniques. By way of example, Fig. 4 shows a diastolic and systolic transverse cross-section of the left ventricle. Though in this single frame representation real-time motion is lacking, the symmetrical contraction of the left ventricle is clearly shown.

Valvular heart disease In mitral stenosis alterations are seen in mobility and thickness of the anterior leaflet of the mitral valve. In mild mitral stenosis the anterior leaflet appears stiff, and motion is jerky and decreased in amplitude. There may even be anterior diastolic bulging. With severe stenosis the leaflets are fixed and the entire valve moves as a unit (Fig. 5, 6, and 7). Except for some cases with mild mitral stenosis, one sees the posterior leaflet of the mitral valve moving in the same direction with the anterior leaflet in diastole instead of in the opposite direction, as occurs, normally. A fibrotic and/or a calcific valve is indicated by dense, thickened echoes most apparent in the anterior leaflet (Fig. 5, 6, and 7). The enlarged left atrial cavity is usually well delineated; its cross-sectional dimension is larger than the aortic diameter and the increase is proportional to the degree of enlargement (higher LA/Ao ratio) (see Fig. 5, 6, and 7). With pulmonary hypertension, the right ventricular cavity is enlarged and the tricuspid valve becomes visible. The presence of concomitant mitral regurgitation in patients with mitral stenosis cannot be diagnosed with the multiscan system. However, in some cases with predominant mitral regurgitation, an increased excursion of the anterior leaflet of mitral valve is seen. The presence of an enlarged left atrium together with an increased left ventricular volume supports further the diagnosis of mitral regurgitation.

An exaggerated movement of the amplitude of the anterior leaflet of the mitral valve is seen in patients with prolapsing mitral valve syndrome during diastole. Actual prolapse in systole of the anterior leaflet past the posterior leaflet has been seen in two patients. The posterior leaflet of the mitral valve rarely shows this excessive movement. Thickening, calcification, and decreased mobility of the cusps can readily be seen in aortic valve disease (Fig. 5, 6, and 7). In severe calcific aortic stenosis, the valve appears as a series of dense, thick echoes in diastole which separate incompletely during systole. In mild aortic stenosis, either an immobile anterior (right coronary) cusp or posterior cusp can be seen (Fig. 7). Concomitant features are poststenotic dilatation of the aorta and increased left ventricular wall thickness.

Coronary artery disease A general qualitative assessment of the state of left ventricular function can be made immediately from cardiac size, shape, and wall motion. In general an enlarged left ventricle has a more round geometric shape while its dimensions are increased. The motion pattern can be studied, and localized or generalized disorders of contraction detected. The sagittal long-axis cross-section shows the interventricular septum and the

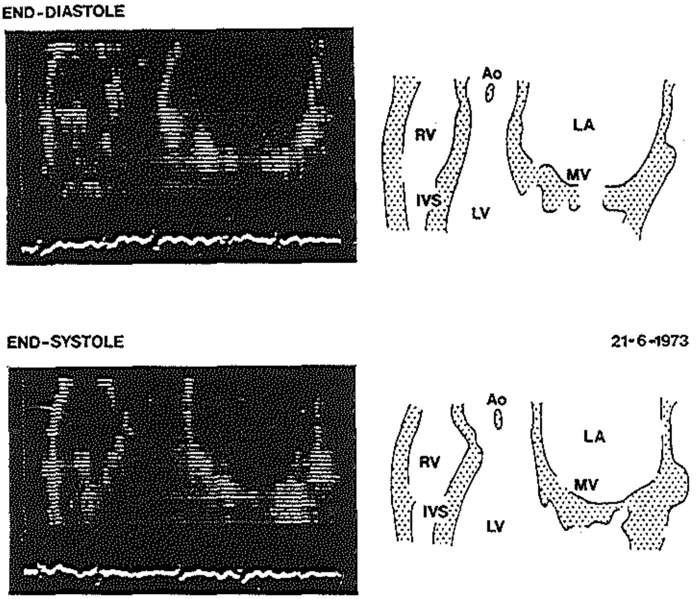

FIG. 5 *End-diastolic and end-systolic frames in a patient with severe calcific aortic and mitral stenosis. Both the anterior and posterior mitral valve leaflets are fixed and the entire valve (MV) moves as a unit, anteriorly in end-diastole, and posteriorly in end-systole. The immobilized calcified aortic valve remains visible during the whole cardiac cycle in the middle of the aortic (Ao) root. (RV = right ventricle; LV = left ventricle; IVS = interventricular septum.) The left atrium is extremely large.*

left ventricular posterior wall. By transverse scanning along the long axis, extensive sections of the left ventricle become accessible for study. Most difficult to display are the apex and part of the anterior wall merely because they are outside the pericardial window. Regional akinesis, hypokinesis, or dyskinesis can be recognized when the behaviour of these areas is compared to the normal or exaggerated contraction of the rest of the left ventricle. Furthermore, quantitation of left ventricular volumes and calculation of ejection fractions is possible with the area-length method.

Congenital heart disease Since cardiac structures and their relations are visualized without distortion with the multiscan technique, cross-sectional anatomy can be assessed. This makes the diagnosis of congenital malformations a major potential application. Thus far, however, our experience has been limited. Mitral-aortic and septal-aortic continuity or discontinuity and the size and orientation of the great vessels relative to the position of the ventricles are visualized, providing important information in many forms of complex cyanotic congenital malformations. Septal overriding of an enlarged aorta has been observed in patients with tetralogy of Fallot.

In patients with small left-to-right shunts no specific abnormalities were seen. With larger shunts, however, enlargement of the right ventricular chamber because of the volume overload becomes apparent. The most specific changes are related to the interventricular septum. The interventricular septum commonly runs posteriorly instead of anteriorly from the aortic root in the presence of a significant shunt lesion (Fig. 8). Systolic anterior or paradoxical septal motion has been described as a reliable finding in right ventricular overload and can be seen clearly with the multiscan display. We have the impression that the paradoxical motion never involves the whole intraventricular septum. The upper part moves always anteriorly and the

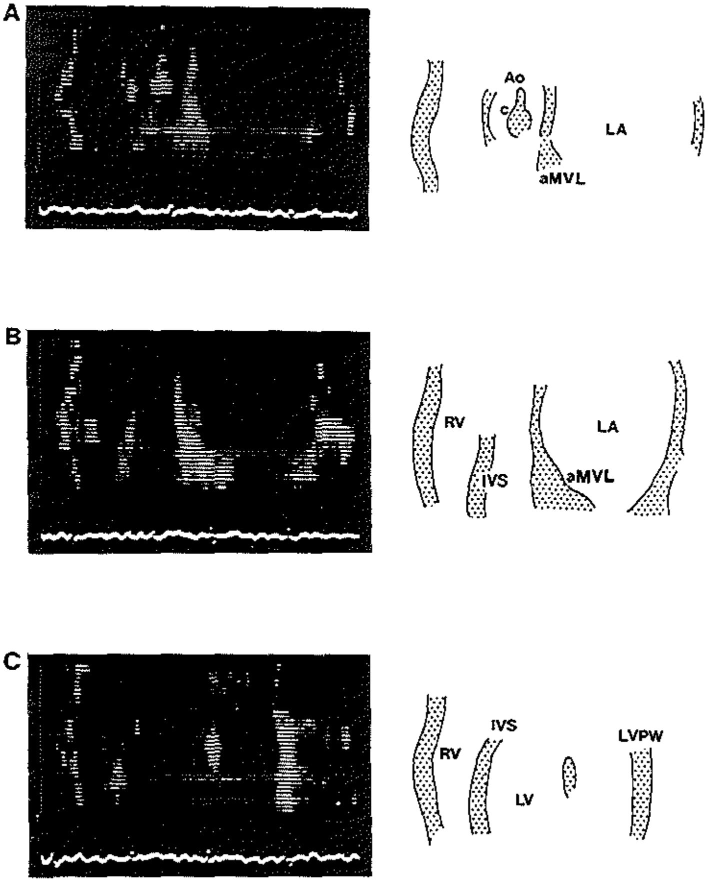

FIG. 6 *A transverse scan in the same patient as shown in Fig. 5. Panel A shows that cross-section where the root of the aorta (Ao) is visualized with a dense thickened echo of the calcified cusps (c). Part of the calcified anterior mitral valve (aMVL) is seen in continuity with the posterior aortic wall. The much enlarged left atrium (LA) is visualized posterior to the aorta. In an intermediate position (panel B), the interventricular septum (IVS) is seen at the same depth as the anterior aortic wall in panel A demonstrating septal-aortic continuity. There is a dense thickened anterior mitral valve echo (aMVL) and the left atrium is still visible at this level. Further tilting of the transducer (see position A in Fig. 1) shows a cross-section through both the right ventricle (RV) and left ventricle (LV). A dense echo, most probably of calcified chordae, is visible in the left ventricular cavity.*

lower part posteriorly. The point around which the interventricular septum pivots is lower in the septum when larger shunts are present but no systematic study has been undertaken yet. In all patients with right ventricular chamber enlargement, the tricuspid valve is visualized and has increased motion amplitude. In the record shown in Fig. 8 the pulmonary cusps were visualized also.

Cardiomyopathies In the hypertrophic types, recently unified and described as asymmetrical septal hypertrophy (Henry, Clark, and Epstein,

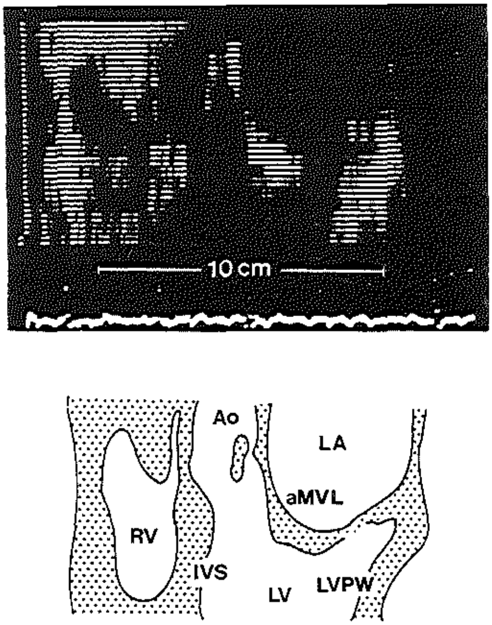

FIG. 7 *Long-axis cross-section in another patient with calcific aortic and mitral valve disease. A dense echo of the posterior coronary cusp of the aorta remains visible during systole. (RV = right ventricle; IVS = interventricular septum; Ao = aorta; LA = left atrium; aMVL = anterior mitral valve leaflet; LV = left ventricle; LVPW = left ventricular posterior wall.)*

1973), the most apparent features are increased thickness of the interventricular septum and a banana-like shape of the small-sized left ventricle. Motion of left ventricular walls is normal or even exaggerated. An enlarged left atrium points to coexistent mitral regurgitation. Where abnormal systolic motion of the anterior leaflet of the mitral valve was present, it resulted in a narrow left ventricular outflow tract in those patients in whom an outflow gradient was found during left ventricular heart catheterization. Fig. 9 shows the typical appearance of the multiscan echocardiogram in a patient with asymmetrial septal hypertrophy and a left ventricular outflow gradient. Asymmetrical septal hypertrophy is an instance which strikingly illustrates the unique qualities of the multiscan for instantaneous and complete diagnosis. In the dilated or congestive types of cardiomyopathies a large left ventricle of globular shape with generalized hypokinesis is so characteristic that the diagnosis is made immediately (Fig. 2 and 10). The increased distance between the anterior leaflet of the mitral valve and the interventricular septum in contrast to the decreased distance in the hypertrophic types is another characteristic finding. In all patients studied the left atrium was greatly enlarged (Fig. 2).

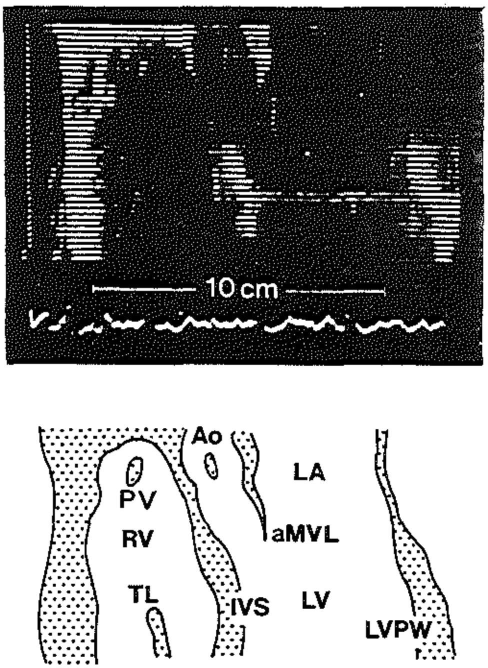

FIG. 8 *A long-axis cross-section in a patient with atrial septal defect (secundum type) and pulmonary hypertension. A greatly dilated right ventricle (RV) is apparent and the movements of both the tricuspid valve (TL = tricuspid leaflet) and pulmonary valve (high in the right ventricle) were seen on the oscilloscope display. The structures were identified by their typical motion pattern on the M-mode recordings made from the selected single elements passing through these structures. The interventricular septum (IVS) runs posteriorly instead of anteriorly as seen normally (see Fig. 3). This is a common finding with right ventricular dilatation. Note also the enlarged left atrium (LA). (Ao = aorta; aMVL = anterior mitral valve leaflet; LV = left ventricle; LVPW = left ventricular posterior wall.)*

Pericardial effusion A few patients with pericardial effusion were studied. Small amounts of fluid, detected with the single element technique as

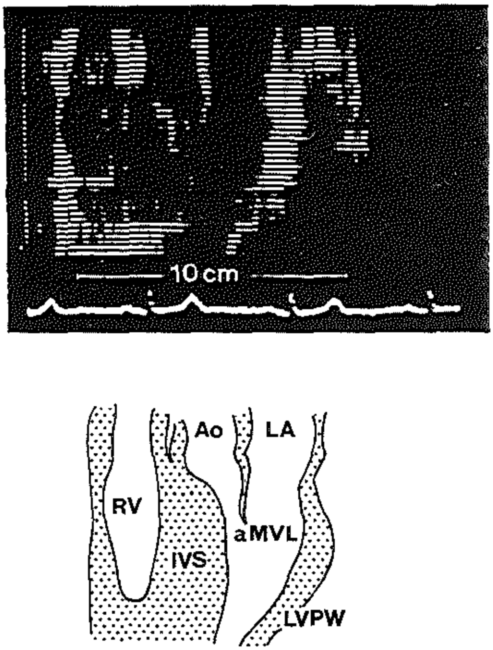

FIG. 9 *The typical features found in patients with asymmetrical septal hypertrophy are seen on this cross-section. The thickened septum (IVS) as compared to the left ventricular posterior wall (LVPW) is clearly shown and the banana-like shape of the left ventricle is striking. The frame shows a systolic cross-section and the anterior mitral valve leaflet (aMVL) is in an abnormal anterior position, close to the interventricular septum instead of in a posterior and superior position as seen normally. This causes narrowing of the left ventricular outflow, and in this patient an outflow gradient of 60 mmHg at rest was measured during cardiac catheterization.*

an echo free space between posterior epicardium and pericardium during systole, were not visualized with the multiscan. Larger amounts, seen on the M-mode as an anterior and a posterior echo free space, were always detected with the multiscan. An example is given in Fig. 11. This patient had massive pericardial effusion and a large amount of fluid in the anterior pericardial space. In this case, an oscillating anterior-posterior movement of the whole heart in the pericardial fluid was seen. This total cardiac displacement has been described as a common finding when large pericardial effusions are present (Feigenbaum, Zaky, and Grabhorn, 1966).

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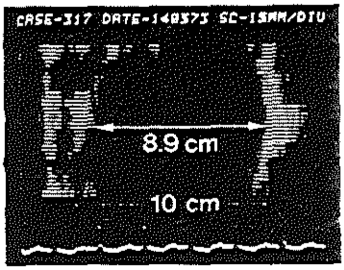

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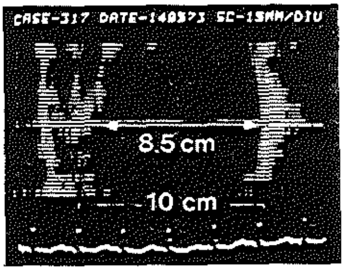


FIG. 10 *End-systolic and end-diastolic long-axis cross-sections obtained from a patient with a dilated congestive cardiomyopathy. An extremely large ventricle of a globular shape is seen. Generalized hypokinesis was immediately diagnosed from the oscilloscope display and is here shown by the small changes of a left ventricular dimension between end-diastole and end-systole (8·9 cm vs. 8·5 cm).*

Applications for quantitation and dimensional measurements

In a first attempt to employ the system for quantitative analysis, a comparison was carried out in 23 patients of the aortic root diameter measured from calibrated angiograms and from videotape recordings of multiscan images. A significant correlation was found ($P < 0{\cdot}001$, χ^2 test) with a small standard error (Kloster *et al.*, 1973a). When the interventricular septum and left ventricular posterior wall are visualized and recorded simultaneously, dimensional analysis of the left ventricle is possible. On records from the line scan recorder with a selected single line passing through the left ventricular cavity good definition of the left side of the interventricular septum and the posterior left ventricular endocardium is usually obtained (Fig. 12). By selection of the most representative diameter of the left ventricle, it should also be possible to calculate the

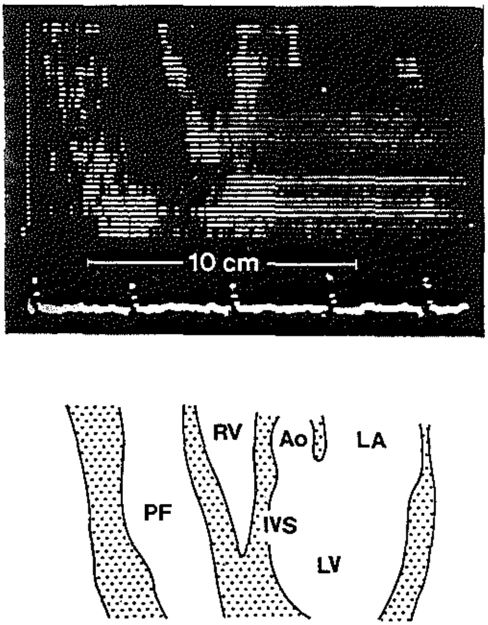


FIG. 11 *In this patient with massive pericardial effusion, a large echo-free space is recognized anterior to the heart. (PF=pericardial fluid.) The whole heart was displaced and the posterior heart wall was at a depth of about 16 cm. On the oscilloscope display, an oscillating movement of the entire heart was demonstrated.*

rate of midwall circumferential fibre shortening, as suggested by Paraskos *et al.* (1971) and Cooper *et al.* (1972). In addition, data on cardiac volumes with the echocardiographic formulae proposed by Popp and Harrison (1970), Pombo, Troy, and Russell (1971), and Feigenbaum *et al.* (1972) should be obtainable. As it is also possible to record both the endocardium and pericardium separately, by changing the depth gain compensation, measurements of left ventricular posterior wall and interventricular septal thickness come within reach (Fig. 12). However, since multiscan provides instantaneous left ventricular cross-sections suitable for the calculation of left ventricular volumes from generally accepted and anatomically correct angiographic formulae, this approach was first pursued (Greene *et al.*, 1967; Sandler and Dodge, 1968). When the whole left ventricle is visualized it proved possible to measure the long axis and to outline the left ventricular cavity. Fig. 13 shows an end-diastolic and end-systolic frame used for these measurements. To assess the possibilities and feasibility of this method, left ventricular volumes calculated from multiscan frames and quantitative left ventricular angiograms have been compared in 14 patients.

Multiscan end-diastolic volume showed a high degree of correlation with angiographic volumes (mean values 90·4 versus 95·9 ml/m^2; r=0·92). However, end-systolic volumes determined by multiscan were consistently larger than those determined by angiography (56·2 versus 44·5 ml/m^2; r=0·89), so that the stroke volume by multiscan was consistently smaller. As a result the left ventricular ejection fraction by multiscan as compared to that by angiography is lower. This was also found with other techniques of volume measurement which similarly indicate that assessment of end-systolic volume by angiography shows a systematic underestimation of volume (Bartle and Sanmarco, 1966; Hugenholtz, Wagner, and Sandler, 1968). The methods and results will be discussed elsewhere in greater detail (Kloster *et al.*, 1973b).

Discussion

At present there are many echocardiographic techniques available to obtain two-dimensional information about the heart. All techniques based on B-scan (Ebina *et al.*, 1967; Kikuchi and Okuyama, 1970; King, 1973) produce 'frozen' images of the heart at a selected part of the cardiac cycle. As many cardiac cycles are required to construct the image, changes in cardiac position and difficulties caused by irregularities in rhythm render these systems suboptimal for clinical application. Äsberg (1967) obtained two-dimensional information with a mechanical mirror system rotated over an arc of about 30° at a rate of seven frames a second. Hertz and Lündström (1972) obtained 16 frames a second with a similar system. For these mechanical rocking systems limited scanning rates, bulky transducer size, difficult transducer aiming, and image distortion are some of the problems. Gramiak *et al.* (1972) developed a technique which produces ultrasonic cross-sectional images of the heart in motion. However, cine-ultrasound cardiography is time consuming and there is some image distortion as the wedge-shaped section of the heart obtained by the sound beam is represented in a rectangular format. None of these drawbacks pertains to the multiscan system presented here. Thus, the capabilities of diagnostic ultrasound are expanded by instantaneous two-dimensional moving cross-sections of the heart. Furthermore, when compared to the negative shadow images obtained with angiography, there is the advantage of a positive cross-section of the heart with all its structures visualized in a manner familiar

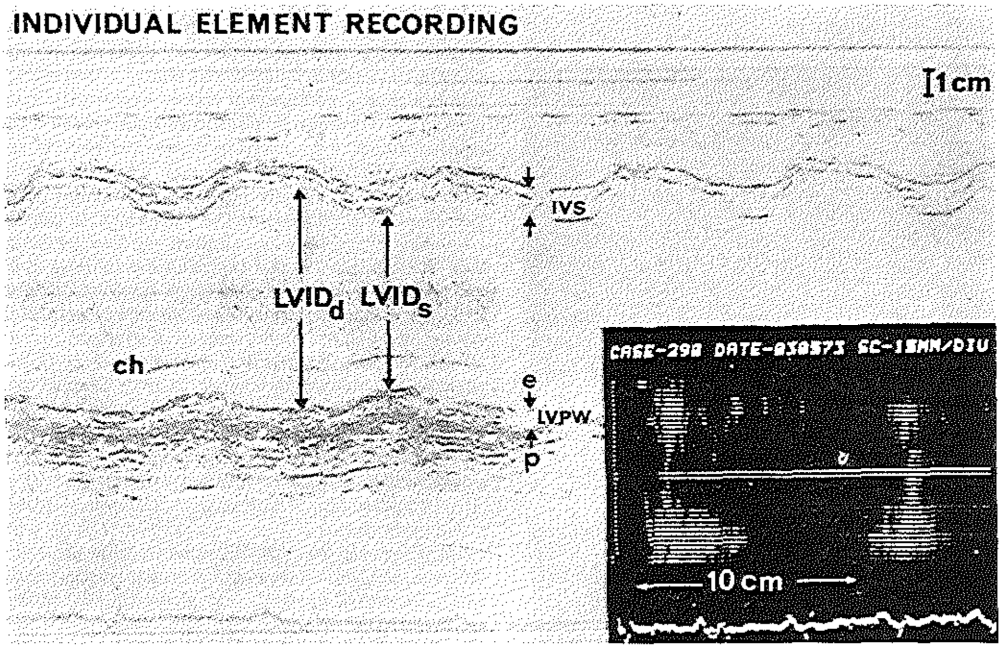
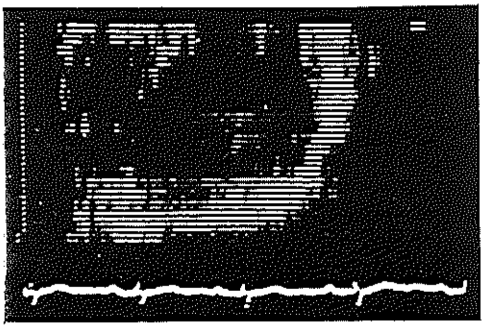


FIG. 12 *This M-mode tracing is recorded from a single element of the multiscan transducer. The selected signal is the bright line running through the left ventricular cavity, seen on the insert photograph. The patient has coronary artery disease with a hypokinetic posterior wall and an enlarged left ventricular cavity. Both the interventricular septum and left ventricular posterior wall are recorded with satisfactory resolution. Changing the time gain compensation allows measurements of interventricular septum and left ventricular posterior wall thickness. This record is most suitable for dimensional left ventricular measurements and calculation of derived volume data. (*$LVID_s$ *and* $LVID_d$ *= left ventricular internal dimension during systole and diastole; ch = chordae echo; e = endocardium; p = pericardium; IVS = interventricular septum, LVPW = left ventricular posterior wall.)*

to those who know cardiac anatomy. In addition, information on the relations of cardiac structures is provided without distortion.

Congenital malformations, especially in newborns and infants, offer a major potential application for the system particularly when the risk of unnecessary catheterization may be avoided by appropriate preselection of candidates by means of the echoscan. Qualitative valve motion analysis in valvular heart disease and evidence of thickening and/or calcification in cases with rheumatic mitral and aortic valve disease is immediately available. Furthermore, the size, shape, and contraction pattern of the left ventricle can be interpreted and a qualitative assessment of the left ventricular function made. Evaluation of left ventricular function and detection of localized disorders of wall motion in patients with coronary artery disease is a most promising area for investigation. When the long-axis cross-section and a transverse scan are performed, a large part of the left ventricle becomes accessible for study.

While the most unique application of the system is the study of the dynamics of cardiac contraction and valve motion, it allows also quantitative measurements of cardiac dimensions and left ventricular volumes. This is an area of major interest in clinical cardiology today. Despite the excellent correlations between echo and angio volumes found in some studies using the single element echocardiographic techniques, it is not known if the echo axis truly approximates the angiographic short diameter of minor axis of the left ventricle (Pombo *et al.*, 1971;



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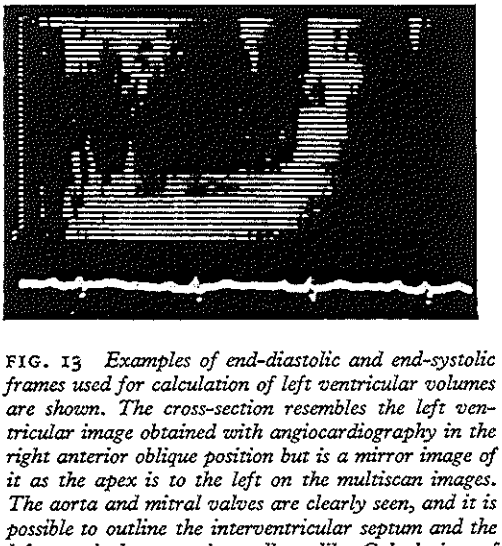

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FIG. 13 *Examples of end-diastolic and end-systolic frames used for calculation of left ventricular volumes are shown. The cross-section resembles the left ventricular image obtained with angiocardiography in the right anterior oblique position but is a mirror image of it as the apex is to the left on the multiscan images. The aorta and mitral valves are clearly seen, and it is possible to outline the interventricular septum and the left ventricular posterior wall readily. Calculations of volumes are performed using the area-length method.*

Feigenbaum *et al.*, 1972). Indeed, to calculate the volume from echo-determined left ventricular dimensions, one has to assume that the measured dimensions have constant relations to the axes of the left ventricle both at end-systole and at end-diastole. This is not true for dilated ventricles and patients with segmental abnormalities of contraction due to coronary artery disease. The multiscan system appears to offer a ready solution, since the precise location of each echo axis through the left ventricle is known. As both the septal and posterior left ventricular endocardial echoes are displayed on M-mode recordings of a selected element from the transducer, this information is also present on the two-dimensional images (Fig. 12). Therefore a real cross-section of the left ventricle is obtained comparable to the shadow of the left ventricle during angiography in the right anterior oblique position. The area-length method proposed by Greene *et al.* (1967) can be applied and, since both length and area are measured, this method is applicable to ventricles of all sizes and shapes. The initial results of studies in 14 patients are encouraging. End-diastolic volumes calculated from multiscan frames agree well with angiographically calculated volumes. There is a consistent overestimation of the multiscan end-systolic volume compared to angio, resulting in a smaller stroke volume and an underestimation of left ventricular ejection fraction. However, a systematic underestimation of end-systolic volumes by cineangiography has been found with other indicator dilution methods (Hugenholtz *et al.*, 1968; Bartle and Sanmarco, 1966), and may simply reflect methodological differences. The fact that these qualitative analyses and quantitative measurements can be made in a non-invasive manner with an unlimited frequency opens new areas for clinical investigation as well as for teaching and training.

Some problems have still to be resolved in displaying and recording the multiscan information. Different display and recording methods are still under evaluation (Fig. 14). Considerable technical improvements in the instrument are also possible and will increase the capabilities of the system.

In general, the multiscan is subject to the same physical limitations of sound transmission and reflection as conventional single element systems (Bom, 1972; Bom *et al.*, 1973a). Significant distortion of images behind ribs because of higher ultrasound velocities in bone has not been observed. Insufficient lateral resolution, a problem of all echo systems, continues to be a limitation (Bom *et al.*, 1973a). Also echoes originating from side lobe beams can deform the display of specific structures. Though these side lobe effects were negligible in *in vitro* experiments, their overall effects in the clinical situation remain unpredictable (Bom, 1972), and practical experience will have to be collected before a definite statement as to their influence can be made. The commonest cause of failure is the presence of only a small pericardial window, for example, when pulmonary emphysema or an anterior chest wall deformation is present. Intervening dense tissue, such as heavily calcified ribs, may obscure

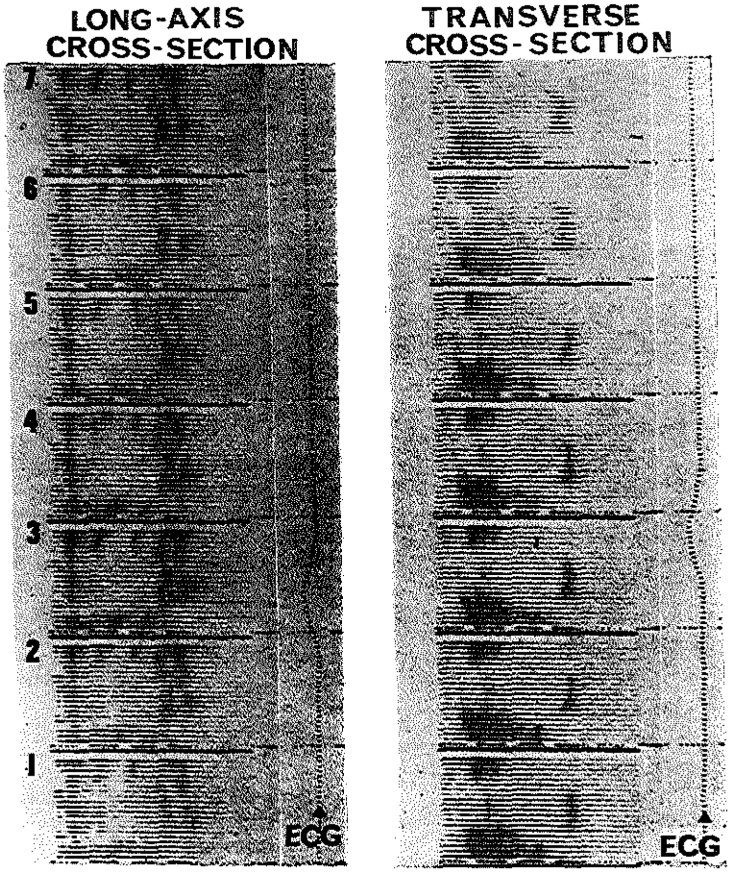

FIG. 14 *Seven cross-sections recorded on the Honeywell 1856 Visicorder with the transducer in the long-axis and transverse positions are shown together with the electrocardiogram. The format of the images is small but the definition of the echoes is quite good. These 'stampsize' pictures are recorded at 25 frames/sec.*

parts of the image. This factor is operative especially in elderly people. However, considerable detail remains visible between the obscured areas, and structures can be recognized by extrapolation. Difficult or unsatisfactory studies occur particularly with a large anteroposterior chest diameter resulting in greater distance of the structures from the probe.

From the results presented in this paper one may conclude that multiscan echocardiography is a valuable extension of the now widely accepted single element technique and will become a fundamental addition to non-invasive methods for the study of the normal and diseased heart.

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CHAPTER 7

EVALUATION OF STRUCTURE RECOGNITION WITH THE MULTISCAN ECHOCARDIOGRAPH

A COOPERATIVE STUDY IN 580 PATIENTS

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Abstract—Real time, two-dimensional, images of the heart can now be obtained with the multiscan ultrasound system recently introduced. To assess the clinical usefulness of this technique a cooperative study was carried out in four cardiac centers. This paper describes the experience with and the results in 580 patients with different ages and disorders.

Since a unique feature of multiscan is the instantaneous display of cardiac geometry and anatomy, structure recognition was chosen as the most important parameter to analyze. Image quality or recognition levels for eight specific cardiac structures were documented. Results also include recognition levels for different age and disease groups and a comparison between the four centers. In addition, information was gathered on the general diagnostic capability of the multi-element system and the possibility of quantitation of dimensions.

Aortic root, anterior mitral valve leaflet and left ventricular posterior wall were the structures most readily recognized. Excellent or good images were seen in two-thirds of all patients. Best visualization was obtained in young patients. A positive diagnosis could be made or confirmed in about one half of the patients with valvular, congenital or myocardial disease and in nearly all patients with pericardial effusion. As experience was gained, the diagnostic importance of the technique shifted from structure recognition towards analysis of left ventricular function.

It is clear that the multiscan system does allow excellent orientation and yields quick, non-invasive information of pertinent clinical value. The method provides an immediate overall impression of the heart. It is foreseen that this technique in combination with existing time-motion recording methods will expand the use of echocardiography drastically.

Key words: Echocardiography, Non-invasive techniques, Ultrasound, Echotomography.

INTRODUCTION

A NEW ultrasound two-dimensional cardiac imaging technique has been developed for non-invasive cardiac diagnosis. Details of the apparatus have been described elsewhere (Bom *et al.*, 1971; Bom *et al.*, 1973). In contrast to stopaction techniques (Ebina, 1967; Tanaka, 1971; Gramiak, 1973; King, 1973) which summate echoes of the heart structures in a single plane, this new method is based on the rapid

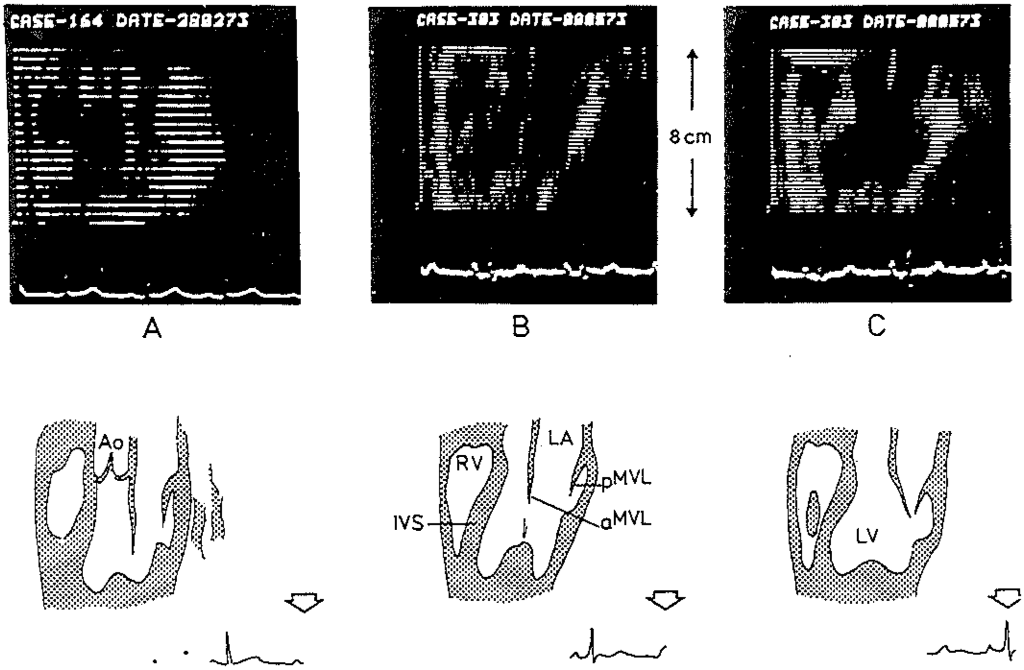

Fig. 1. Echograms obtained with the multiscan technique. A schematic image construction is shown in the bottom diagrams (Ao = aorta; IVS = interventricular septum; LA = left atrium; LV = left ventricle; RV = right ventricle; aMVL = anterior mitral valve leaflet; pMVL = posterior mitral valve leaflet). The timing in the cardiac cycle is indicated by the arrow on the electrocardiogram. The echograms show respectively the 20 line image quality as used in this study (A) and more recent images as obtained with a 40 line display (B and C). Due to limited transducer length (8 cm) the apex is not shown on the echograms when the probe is positioned to show the aortic region.

successive transmission of sound pulses and reception of echoes by 20 small elements positioned in a row and contained in a transducer of 8 cm length and 1 cm width which can readily be aimed in different directions. The echoes are displayed on an oscilloscope as brightness modulated dots on lines where line height corresponds to element position in the transducer. The image covers 8 × 16 cm. With 20 line images the frame repetition rate is approximately 150 frames/sec.

Preliminary feelings concerning the advantages of two-dimensional display methods have been described recently (Roelandt *et al.*, 1973, 1974; Kloster *et al.*, 1973). Excellent orientation could now be combined with a direct overall impression of a moving cross-section through the heart. Two standard transducer positions have been established. One position produces a sagittal cardiac cross-section in the plane of the septum (see Fig. 1). The other position shows a horizontal section across the ventricles. The importance of a scan technique in the transverse position is assessment of congenital malformations verifying mitral aortic and septal aortic continuity and normal or abnormal great vessel orientation. Various recording techniques and an extensive discussion on the limitations of this two-dimensional image system have been described elsewhere (Bom *et al.*, 1973). It was felt that poor lateral resolution was particularly bothersome in a two-dimensional system. As a result details of deeper structures are sometimes hard to recognize.

From an early stage in the multiscan development it was realized that this method would help overcome one of the major limitations of conventional echo techniques. These are due in part to the use of single element transducers where the narrow sound beam does not yield information of adjacent structures. This results in orientation problems which in turn require a high degree of experience. The limited use of conventional technique for diagnostic purposes in complex congenital malformations is an example of this aspect. No immediate overall impression of cardiac dynamics can be obtained from the time-motion registration as recorded with the conventional technique.

The multiscan system yields best results with direct observations from the oscilloscope. This does allow an overall impression of the heart. The additional spatial information also greatly facilitates orientation and thereby recognition of echo origin.

Future combination of both multiscan two-dimensional direct visualization with conventional single element time-motion recording was envisaged from the start. When early in 1973, the prototype instrument became available for evaluation, no "conventional wisdom" existed as to which structures could be easily recognized. It seemed thus important to obtain more information of the recognition capabilities of the new multiscan technique alone. It was also not known in which type of patient or disorder the apparatus could be applied with greatest usefulness. It seemed very important therefore to explore the capabilities of the instrument on a larger scale and preferably with several independent investigators. The purpose of this study thus could be described as the first evaluation of the multiscan technique, all by itself, with emphasis on structure recognition capabilities. To accomplish this goal, the instruments were evaluated in four separate clinics, in which each of the responsible investigators, while experienced in the use of conventional ultrasound for diagnostic purposes, was unfamiliar with the new apparatus. The present study contains the description of their findings with the multiscan technique in 580 patients with a large spectrum of disorders.

METHODS AND MATERIALS

The cooperating centers were located in London (Hammersmith Hospital), San Diego (University Hospital), Stanford (Medical Center) and Rotterdam (University Hospital, Thoraxcenter). The instrument was identical for all centers and contained the multiscan prototype with oscilloscope display and video recording facilities. The instruments were supplied with 2·25 and 4·0 MHz probes. Data were collected on a standardized form from February 1973 to May 1973. For each patient a form was completed which included descriptive information about the patient, the recognition level of eight cardiac structures, the possibility of making a diagnosis directly from the display, and an estimate of quantitation (see Appendix). Structures such as pulmonic valve which are rarely seen with ultrasound were excluded from the form. During the study each patient was examined on only one occasion.

Since the method was new and unfamiliar it was anticipated that the answers to some questions might depend strongly on the investigator's ability to develop techniques and new criteria. Results would strongly depend on individual judgement factors. To minimize this effect the forms were completed according to prospective criteria. Structure recognition grading was to be selected between "excellent" and "not seen".

As an example, for the aortic root and cusps the grading was:
excellent : if root was excellently visualized and cusps clearly visible in diastole and partially in systole
good : if root well seen, cusps clearly visible in diastole
fair : if root clearly outlined, cusps barely or intermittently visible
poor : if root fuzzy and indistinct
none : if not seen.

For the mitral anterior leaflet the grading was:
excellent : if clearly visible over essentially the complete length of the cardiac cycle
good : if clearly visible, but obscured in a minor part of the cardiac cycle
fair : if visible but obscured in an appreciable portion of the cardiac cycle
poor : if barely visible
none : if not seen.

All data were coded and recorded on punch cards. The editing program stored data for each center separately. Results were graphically printed out in a variety of parameter combinations, for each center separately and combined. Records are available in each of the 580 patients. Of these 94 were from London, 81 from Stanford, 109 from San Diego and 296 from Rotterdam. Results were reviewed by all investigators at the end of the study.

RESULTS

(a) *Patient material and overall results*

Patients have been divided in eight age groups (Fig. 2). Group 1 contained infants under one year only, group 8 contained patients over 60 years, and all other groups represent increments of 10 years of age. With the exception of group 1, the patients from Rotterdam and Stanford are well distributed in all age groups. The patient population from London contained 60 per cent patients older than 41 years. In San Diego on the other hand 67 per cent of all patients were less than 20 years old. The accumulated data show good representation over all age groups.

In Fig. 3 a subdivision vs disease is shown. From 580 cases approximately 25 per cent were patients with congenital disease. Many of these patients were from the Pediatric Cardiology group at the University Hospital in San Diego. The largest group was made up of patients with valvular lesions (34 per cent).

In Fig. 4 the grading for recognition of eight cardiac structures is shown as calculated from the accumulated cases. Although investigators were requested to report their findings for all eight structures, on the average 521 of the 580 forms were completed correctly. The highest score for correct completion was for the interventricular septum with 539 cases and the lowest score was for the apex of the left ventricle with 483 cases. In Fig. 4 the percentages on the vertical axis indicate the subdivision in various recognition rates as calculated for each particular structure separately.

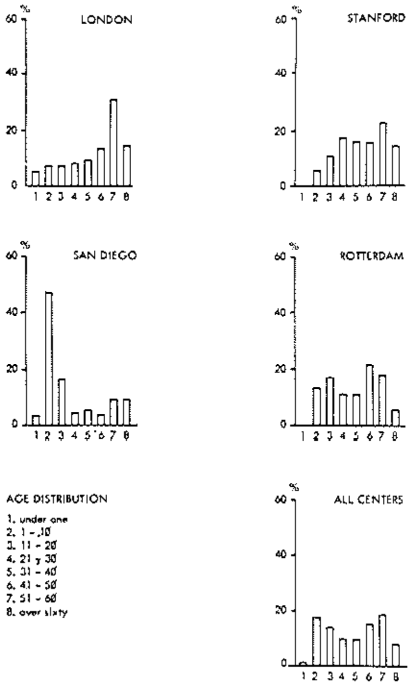

Fig. 2. Subdivision of patient material in age groups. The distribution is shown for each center and for all cases together.

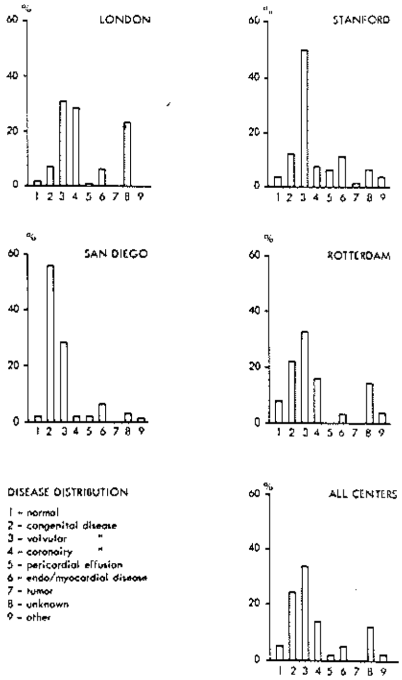

Fig. 3. Subdivision of patient material by disease category, shown for each center and for all cases together.

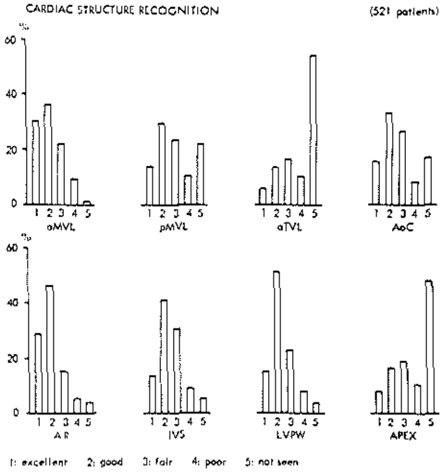

Fig. 4. Cardiac structure recognition level with five gradings ranging from excellent (1) to not seen (5) for eight cardiac structures. Graphs are derived from data representing all patients in four clinical centers. (abbreviations: aMVL and pMVL = anterior and posterior mitral valve leaflet; aTVL = tricuspid valve leaflet; AoC = aortic cusps; AR = aortic root; IVS = interventricular septum; LVPW = left ventricular posterior wall).

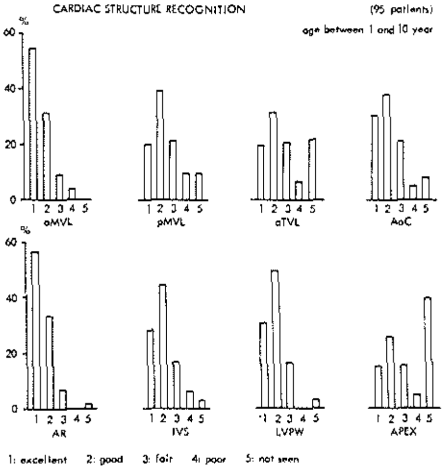

Fig. 5. Cardiac structure recognition with multiscan for patients in the 1–10 year age group.

The aortic root (AR), anterior mitral valve leaflet (aMVL), left ventricular posterior wall (LVPW) and the interventricular septum (IVS) were in general the best recognized structures, with either excellent or good images in 75, 66, 66 and 55 per cent respectively. Only 20 per cent of the tricuspid valve leaflet (aTVL) observations fall in this category. Although the time required to obtain these data is not shown, ready orientation and rapid recognition is usual since with the multiscan technique most important cardiac structures are displayed simultaneously. High scores in column 5 may be due to the investigator's tendency to limit his search for a cardiac structure when it does not seem relevant to the diagnosis of the patient under investigation.

(b) *Structure recognition*

Cardiac structure recognition in the two age groups are compared in Figs. 5 and 6. Figure 5 shows data obtained in 95 patients between 1 and 10 years of age. Figure 6 is based on 94 cases in the age group from 51 to 60 years. Without exception all structures are better visualized in the younger age groups. One of the largest differences occurs with the recognition of the tricuspid valve leaflet. A logical explanation for this finding is the decrease in ultrasound transmission through the sternum in adults. The overall poor recognition of the apex also may be due to unfavourable specular reflections from apical structures. In general, a

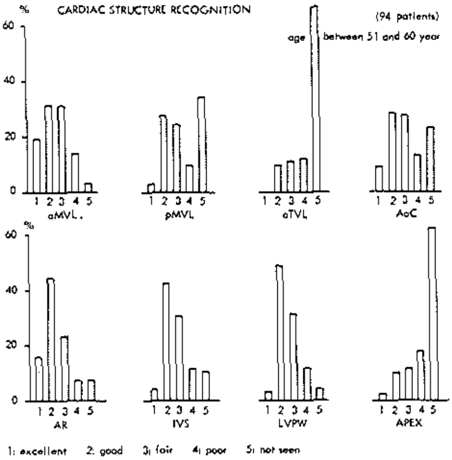

Fig. 6. Cardiac structure recognition with multiscan for patients in the 51–60 year age group.

paucity of calcification in the chest cage of children allowed a large variety of different transducer positions to be used. The analysis of several different cardiac cross-sections allowed therefore a high rate of structure identification. In addition, congenital heart disease represents in a majority of patients the kind of structural abnormalities of the heart, which are particularly amenable to elucidation by cross-sectional echocardiography. Therefore the rate of recognition of structure and of detailed diagnosis is relatively high in the pediatric population with complex anatomic malformations.

Findings in 66 patients with coronary disease are shown in Fig. 7. Similar graphs were produced for patients from various other disease groups. The aortic root, anterior mitral leaflet and left ventricular posterior wall, proved again to be the best landmarks. For instance in patients with valvular disease, either excellent or good recognition grading was obtained in 80, 75 and 62 per cent respectively.

Since length and weight were available for most patients a linearity index was calculated. This was employed as an indication of body habitus. In each age group this index was compared to the standard findings for that group. As an example, Rotterdam patients were divided in three sub-groups, one containing heavy (65 cases), one with normal (103 cases) and one with thin patients (74 cases).

It appeared that the recognition level of either excellent or good for the aortic root, the anterior mitral valve leaflet and the left ventricular posterior wall was consistently higher in the thin group compared to the heavy group 79 vs 59 per cent, 72 vs 42 per cent and 78 vs 67 per cent respectively.

For all structures the recognition level has been plotted as a function of increasing investigator experience judged by the sequential patient case number. This is shown in Fig. 8 for the anterior mitral valve leaflet and the posterior left ventricular wall. From these two examples it may be seen that the mitral leaflet was well recognized from the first patient on. Also a more or less constant recognition level was obtained for the posterior left ventricular wall after the first 30–40 patients. Plots from other

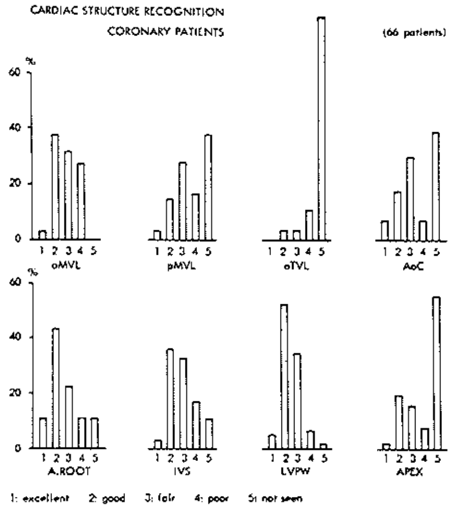

Fig. 7. Cardiac structure recognition in patients with coronary artery disease.

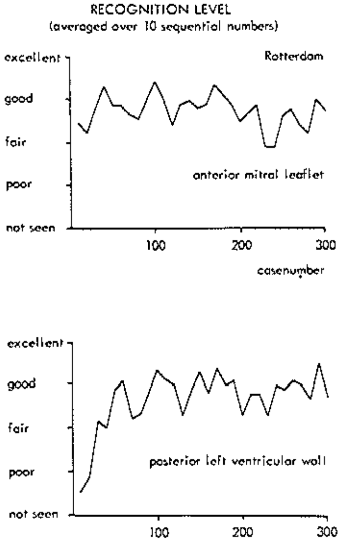

Fig. 8. Recognition level of anterior mitral valve leaflet and posterior left ventricular wall. Average recognition values for each ten consecutive cases are plotted as function of sequential case number, thus demonstrating the time course of recognition level and reflecting the influence of experience of learning.

structures indicated that these were usually recognized at a constant level after an initial brief period of training. Fluctuations in these curves may reflect the investigator's interest in a particular structure, and no general trend could be detected.

For the graphical representation of Figs. 4–7 all accumulated data has been used. Since the apparatus was first available in Rotterdam, the number of patients from this center is higher than the total patient number from all other centers combined. Rotterdam data have therefore biased the study. In order to show the extent of this effect, the individual differences between the centers are shown for the anterior mitral leaflet in Fig. 9. The accumulated results as used so far (A), and a normalized group (B), are given. In the graph the normalization was obtained by an equal weighting of the data of each center in the total result. Although a difference existed between the centers it appeared that in the overall data no significant change occurred in the interpretation if no normalization was used.

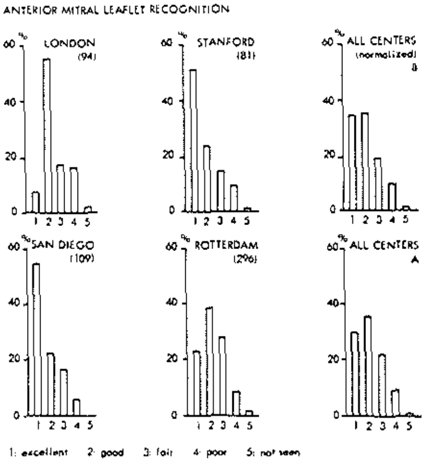

Fig. 9. Recognition level for anterior mitral valve leaflet compared between centers. The normalized plot (B) is obtained by equal weighting for each center. Compared to (A) this shows the influence on the overall results of the higher number of cases documented in Rotterdam.

(c) *Occurrence of poor results. Probe frequencies*

Investigators were asked to report possible reasons when poor results were obtained. In only 14 per cent of all cases any such comment was given. Documented reasons included: a small acoustic window, emphysema, dense calcification of the ribs and insufficient experience.

All instruments were provided with probes of eight centimeter length and a frequency of respectively 2·25 and 4 MHz. The instrument switched automatically to the correct frequency upon insertion of the corresponding probe. When probe frequency was plotted vs age, it appeared that the 2·25 MHz probe was preferred over the 4 MHz probe in 0, 6, 18, 59, 68, 69, 73 and 79 per cent of all cases in the age group 1–8, respectively.

(d) *Clinical usefulness*

Several questions on the evaluation sheet were

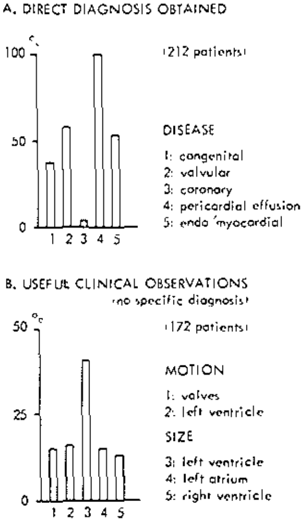

Fig. 10. Panel A—subdivision into diagnostic groups for patients where a direct diagnosis was obtained. Positive answers are displayed as percentage of all patients known to exist in any specific disease group. Panel B—comments about clinically useful information in 172 patients in whom a direct diagnosis was not made from the multiscan. Remarks are subdivided into those concerning motion and those relating to chamber size.

designed to determine the clinical usefulness of the multiscan investigation. In Fig. 10(A) the results from the questions "Could you make a diagnosis from the display?" and "If yes, what?" are shown for various disease groups. A positive answer was obtained in 212 cases. It proved that the best results for direct diagnosis from the multiscan are obtained in patients with pericardial effusion. Valvular diseases, myocardial diseases or congenital malformations were positively diagnosed in about one-half of the cases where they were present. In patients with coronary heart disease the diagnostic yield was relatively low.

A wide variety of additional clinical observations was documented on the forms. Excluding the 212 cases where a direct diagnosis was given (with or without further remarks) from the total of 580, there remained another 172 in this category. Quotations like "enlarged poor contracting left ventricle", "normal left atrium", "well contracting ventricle" or for instance "paradoxical septal motion" etc. were reported. From all remarks a subdivision is shown in Fig. 10(B), where the clinical observations have been subdivided in motion and in size. As may be seen from all remarks the size of the left ventricle was most frequently observed with the multiscan in this patient population.

It should be emphasized that Fig. 10 must be interpreted with caution. The representation of moving cardiac structures in two-dimensions is a new technique and the data represent the initial learning experience for each center as well as subsequent accumulation of diagnostic skill, both of which would tend to positively influence the results later on. However, when the frequency of a direct diagnosis or a pertinent clinical observation are added, it can be stated that clinically useful results in this first series were obtained in 73 per cent of the patients studied. The percentages for individual centers were: London 84 per cent; Stanford 65 per cent; San Diego 86 per cent and Rotterdam 68 per cent.

DISCUSSION

The design and execution of a cooperative evaluation study of a new and untried technique poses many difficulties which influence the eventual outcome. For instance, while at present much more information is available at the outset of this study virtually no knowledge existed whether, and to what extent, the multiscan could assist the physician in his diagnostic efforts nor what real information could be extracted. Therefore four instruments were made available for evaluation. Since none of the investigators knew initially the probe handling technique nor specific diagnostic criteria with moving cross-sectional images the results reflect only a limited and preliminary evaluation of the multiscan apparatus and technique. All investigators felt that the frequency of positive diagnostic findings was therefore quite conservative. On the other hand the recognition grading results do reflect adequately the differences between the recognition rates for various cardiac structures and it was demonstrated that structure recognition and identification were in general uniformly high.

CONCLUSION

This study represents the initial findings on a series of 580 patients investigated with the multiscan in four cardiology centers. The best recognized structures were the aortic root, anterior mitral valve leaflet and the left ventricular posterior wall with excellent or good recognition in 75, 66 and 66 per cent respectively of the patients. In each patient series the recognition rate of specific cardiac structures became constant after an initial brief period of experience. More experience was necessary to recognize dynamic ventricular abnormalities. In this initial series most confidence was felt in diagnosing patients with congenital, valvular, myocardial diseases or pericardial effusion. In most patients with coronary disease important clinical observations on left ventricular function and size were documented. Clinically useful information was obtained in 73 per cent of all investigations. The diagnostic power of the multiscan system will undoubtedly increase when more experience becomes available.

In more recent apparatus* the conventional single element time-motion recording facilities have been fully incorporated in the multiscan system. This combines the advantages of easy structure recognition, good orientation and overall visualization of the moving heart with conventional, well-known, recording facilities. From the experience gained in the study of the first 580 patients with the multiscan alone it is concluded that a new and useful clinical tool has become available which can, combined with single element technique, substantially increase the capabilities of echocardiography.

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APPENDIX

Clinical evaluation form as used during this study

Medical Faculty Rotterdam
Echocardiography

Please mark correct answer

Clinical evaluation Multiscan patient form
1-1-73
leave blank

General data

Institution:	London 1	Stanford 2	San Diego 3	Thorax C. 4	1
name investigator:					
date of investigation (day/month/year):					3

Patient identification

Patient name:				
Patient file code:				
Patient Multiscan number:				9
male 1	female 2			12
birth date (day/month/year):				13
length	cm.	weight:	kg.	19
Clinical diagnoses (in order of importance):				25
Is investigation postoperative?	yes 1	no 2		29

Visual recognition of: (complete for each structure)		1 exc	2 good	3 fair	4 poor	5 none			
Valves	Anterior mitral leaflet								30
	Posterior mitral leaflet								31
	Tricuspid valve								32
	Aortic cusps								33
Other structures	Aortic root								34
	Ventricular septum								35
	Posterior L. V. wall								36
	Apex								37
Other:									38

With poor results: reason:				41
What was optimal frequency?	2.25 MHz 1	4·0 MHz 2		43

Could you make a diagnosis from the display?	yes 1	no 2		44
If yes, what?				45
Could you use data for further quantization?	yes 1	no 2		46
If yes, check which:	L. V. volume			47
	R. V. volume			48
	Atrial size			49
	Mitral motion			50
	Septal motion			51
Other:				52

Comment:

Extrait de :
« PERFORMANCE VENTRICULAIRE GAUCHE CHEZ L'HOMME »
Expansion Scientifique, Paris, 1975

LEFT VENTRICULAR FUNCTION BY MULTIPLE ELEMENT ECHOCARDIOGRAPHY

J. ROELANDT, F. E. KLOSTER, W. B. VLETTER
W. VAN DORP, N. BOM, P.G. HUGENHOLTZ

Echocardiography is now established as a reliable and valid procedure for the non-invasive assessment of left ventricular function [6, 8-12, 18-21]. However, in conventional single element echocardiography, only a selected narrow portion of the heart in depth is plotted as a function of time (M-mode). With this representation, no information about adjacent cardiac structures and their anatomical relationships is obtained. This limits the overall assessment of left ventricular function as no information about the activity of the heart as a whole is obtained. More serious limitations are encountered when ventricular dimensions and volumes are studied. This is due to the uncertainty as to the correlation between the echo and true anatomical axes of the left ventricle especially when changes in ventricular geometry occur like in coronary artery disease. Therefore, several attempts have been made in recent years to obtain more complete anatomical and real-time information about the dynamic function of the left ventricle from an « overview » image such as obtained with angiocardiography [1, 14, 15, 17].

The multi-element ultrasound system is one of the most recent developments and provides instantaneous two-dimensional cross sections of the heart with good resolution at 80 frames per second [3-5]. It is the purpose of this communication to present the examination technique and the application of the system for the evaluation of left ventricular function.

The multiple element system

Technical aspects of the system have been described in previous papers [3-5, 23-25]. The core of the system is the transducer and consists of an 8 cm linear array of 20 fixed ultrasound crystals. Each element in sequence transmits a short acoustic pulse, then receives echoes from the underlying tissues. That element is silent when the next transmits and receives, and so on down the line. Fast electronic switching from one element to another results in a repetition rate of a 160 complete frames per second. The echo signals are displayed on an oscilloscope. The position of the signals

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from each element on the vertical axis corresponds to its position in the transducer. Distance of structures from the transducer is displayed on the horizontal axis and differing intensity of echoes is indicated by varying brightness. Presently, a 40 line oscilloscope image is produced by interlacing two consecutive frames reducing the effective frame rate to 80 frames per second. Anterior chestwall is always to the left of the display. Simultaneously with the cross sectional image, the identification symbols of the patient and his electrocardiogram of the three preceding seconds are displayed. The point in the cardiac cycle is indicated by the right end of the ECG on the display.

Examination technique

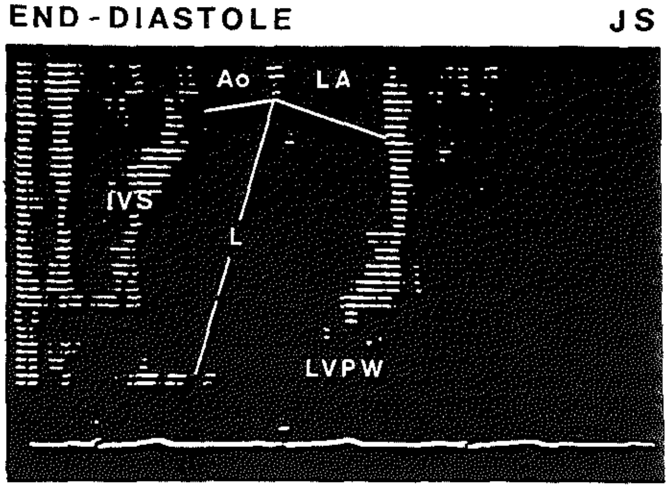
Patients are examined in the supine position with the head of the bed raised about 20° to 30°. Turning the patient slightly on his left side allows better visualisation of the interventricular septum (IVS) and left ventricular posterior wall (LVPW) simultaneously. This is important when dimensional measurements and outlining of the left ventricular (LV) cavity for the calculation of volumes are aimed for. A routine multi element echographic examination always consists of displaying the long-axis cross section first, then a transverse cross section through the LV cavity followed by a transverse scan [18, 23-25].

In the long axis, the transducer is placed obliquely to the left of the sternum with the upper end at the costosternal border. The lower end is angulated laterally about 25° from the midline. This produces a cross section through the long axis of the heart in a sagittal plane from the base of the heart towards the apex (fig. 1).

In the transverse position the transducer is placed to the left of the sternum perpendicular to the long axis position and approximately along the 3rd or 4th intercostal space. The upper end of the transducer is to the patients right and forms the top of the image on the display. The resulting image is a transverse cross section through both the right ventricle (RV) and LV at a ± 90° angle with the long axis of the heart. The LV is posterior to the RV with the IVS at a slight angle from the upper right to the lower left. By tilting the transducer in a superior or an inferior direction, a two-dimensional transverse scan of the heart along the long axis can be performed [25].

Methods and analysis of data

The best images are those directly available on the oscilloscope display at the time of study. Qualitative assessment of the size, shape and motion of the LV as a whole can be performed and the contraction pattern of the LV can be studied in different cross sections. A greater percentage of the LV becomes so accessible for wall motion analysis than with the conventional single plane angiographic techniques. Recordings on magnetic videotape allow playback for these motion studies later but a considerable loss of quality in the individual frames limits the possibility of quantitation.



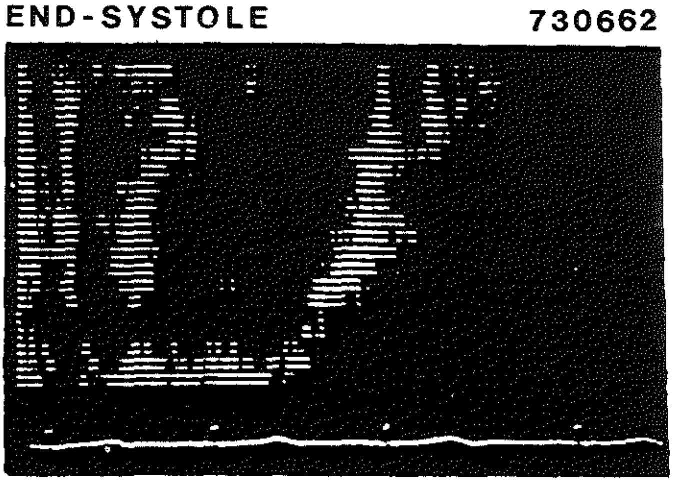


Fig. 1. — End-diastolic and end-systolic frames used for calculation of left ventricular volumes. The long-axis cross sections resemble the left ventricular shadow images obtained with single plane angiocardiography in the right anterior oblique position, but it is a mirror image as the apex is to the left. It is possible to identify the root of the aorta (Ao), a plane across the mitral valve ring, the left ventricular posterior wall (LVPW), the apex and the interventricular septum (IVS). The outline of the left ventricle can be traced and the area determined by planimetry. The long axis (L) can be measured directly. Ventricular volume is calculated using the area-length formula (see text).

For subsequent quantitative analysis, permanent records are made on Polaroid photographs and cinematographic film. The quality of Polaroid photographs of individual frames made from the oscilloscope screen is quite good. Triggering from the QRS complex allows the recording of these frames at selected moments in the cardiac cycle such as end-systole (ES) and end-diastole (ED) (Fig. 1).

The cross sections obtained with the transducer is the long axis position, resemble the shadow images obtained after opacification with cineangiography of the LV in the right anterior oblique position (Fig. 1). It is possible to outline the LV cavity directly from the Polaroids going across the aortic root and mitral annulus down the LVPW, apex and up to the IVS. The long axis is measured from the junction of the anterior mitral leaflet with the aorta to the apex (Fig. 1). The area of the LV cross section is then measured by planimetry. These measurements have to be corrected for magnification. The height of a frame always corresponds to 8 cm (size of the transducer). Depth calibration can be performed with a calibrated perspex block. Markings on the oscilloscope screen allow adjustment to the appropriate 8 × 16 cm viewing area. By means of the angiographic area-length method proposed by Greene et al. [13], LV volumes can be calculated. The use of the measured cross sectional area of the LV will account to a certain degree for variations in the geometric shape of the LV while measurements of the long axis eliminate the need to rely upon assumptions such as that it is twice as long as the short axis. It is known that this assumption holds only for normal sized ventricles [22, 26]. In conventional echocardiography volumes are approximated by cubing the measured echo axis. The area length formula used for the calculation of volumes from the two-dimensional cross sections is : $V = K \frac{8A^2}{3\pi L}$ where A is the cross sectional area in cm^2 ; L the long axis in cm and K the cubed calibration factor. LV ejection fraction is calculated as (ED - ES) volume divided by ED volume for both echo and angio data.

The original oscilloscope images are also recorded on 16 mm movie film. However, since the camera speed is less than the frame rate of the Multiscan, several echo dots are superimposed on one film frame. This results in smearing. Increasing the film speed to 80 frames per second creates problems with film exposure time and synchronization. The quality of the images is quite good when viewed in motion allowing qualitative assessment of left ventricular dynamics. Recent improvements to the cinematographic film technique allow superimposition of ED and ES contours of the LV and calculation of volumes as well. Localized disorders in wall motion can now easily be demonstrated. Recordings in the M-mode from any selected individual element are also made on the linescan recorder (Honeywell 1856 Visicorder). This combines the two-dimensional orientation facility of the Multiscan with the high resolution single element facility.

Materials

To evaluate the feasibility and reliability of LV volume determinations and the detection of localized disorders of wall motion by multiple element echocardiography, 17 patients were studied and their results compared to the data and volumes calcu-

TABLE I

LEFT VENTRICULAR VOLUMES AND EJECTION FRACTIONS CALCULATED FROM MULTISCAN CROSS SECTIONS AND QUANTITATIVE ANGIOCARDIOGRAMS

Patient no.	Diagnosis	Sex/age	EDV (ml/m^2)		ESV (ml/m^2)		EF %	
			E	A	E	A	E	A
1	CAD	45 M	73	83	41	29	44	65
2	CAD	46 M	87	86	47	34	46	60
3	CAD	61 M	155	162	107	97	31	40
4	normal	51 F	64	77	41	41	36	47
5	AS/AR	50 M	112	107	59	33	47	69
6	CAD	31 M	97	91	42	37	57	59
7	CAD	49 M	90	101	51	45	43	55
8	CAD	33 M	85	97	48	40	44	59
9	CAD	40 M	63	58	37	33	41	43
10	CAD	30 M	84	106	40	51	52	52
11	CAD	49 M	98	108	54	52	45	52
12	MS/MR	42 M	100	100	56	57	44	43
13	CAD	43 M	79	94	54	65	32	31
14	CAD	40 M	79	86	45	34	43	60
15	CM	38 M	90	107	49	48	46	55
16	CAD	43 M	94	79	52	40	45	49
17	CAD	46 M	93	112	58	45	38	60
		N	17	17	17	17	17	17
		Mean	90.8	97.3	51.8	45.9	43.2	52.9
		SD	20.8	21.8	15.7	16.3	6.4	9.8
		r	0.89		0.84		0.58	
			0.94					

(Abbreviations : EDV : end-diastolic volume ; ESV : end-systolic volume ; EF : ejection fraction ; CAD : coronary artery disease ; AS/AR : aortic stenosis and regurgitation ; MS : mitral stenosis ; CM : cardio myopathy).

lated from single plane cineangiograms. Patients studied underwent routine diagnostic left ventriculography and were selected both on the basis of satisfactory LV angiograms for volume calculations and Multiscan studies of suitable quality for quantitative analysis. Multiscan images of satisfactory are obtained in 65 % of adult patients. Of the 17 patients included in this preliminary study, 13 had coronary artery disease, 2 valvular heart disease, one cardiomyopathy and there was 1 normal individual (Table I).

Results

QUALITATIVE ANALYSIS

In all patients important information about LV function was obtained from tis shape, size and dynamic contraction during the initial study. Figure 2a shows a LV

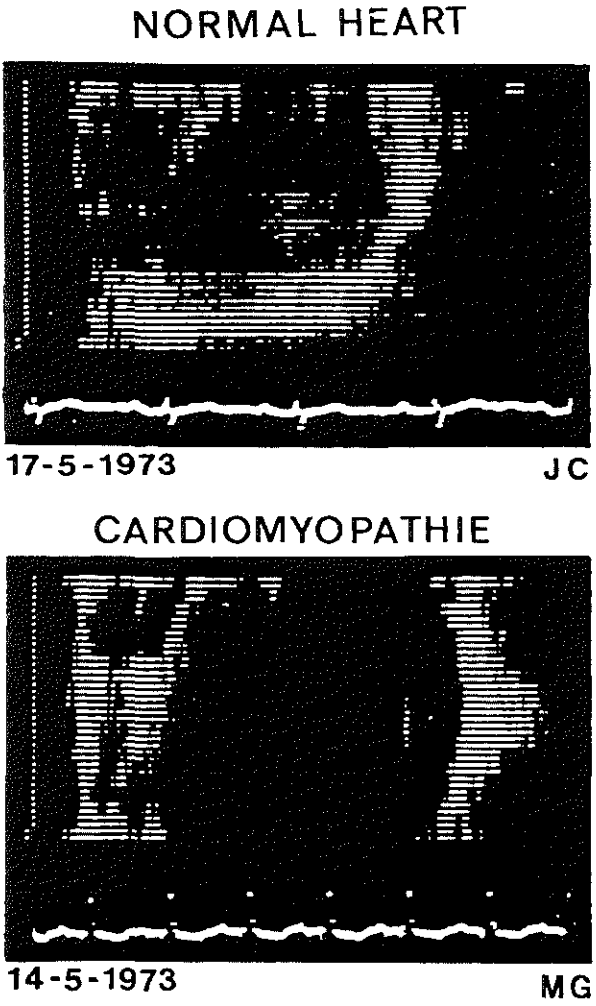


Fig. 2. — The upper panel shows a long-axis cross section at end-diastole in a normal individual. The size and shape of the left ventricle are normal. The lower panel shows the same cross section in a patient with congestive cardiomyopathy. An extremely large ventricle of a globular shape is seen.

of a normal size and shape whereas in figure 2b an extremely enlarged LV of globular shape obtained from a patient with congestive cardiomyopathy is seen. The contours of the LV were traced and superimposed at both ES and ED. Regional hypokinesis and/or akinesis as compared to the normal or exaggerated contraction of the rest of LV was demonstrated in 5 out of 17 patients. Figure 3 shows such an example of ES and ED superimposed LV contours (patient 3). Segmental disease of the myocardium was demonstrated by single plane cineangiography in 6 patients including the 5 patients detected by Multiscan.

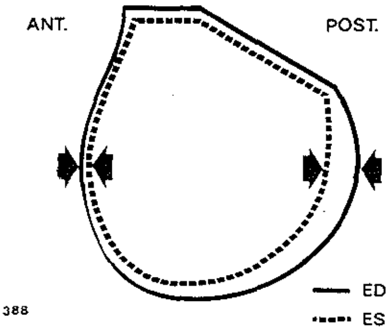


Fig. 3. — Superimposed contours of the left ventricle at end-systole (ES) and end-diastole (ED) are shown. The contraction pattern of the left ventricle can so be demonstrated and akinesis of the septum illustrated.

QUANTITATIVE ANALYSIS

Results are listed in Table I.

Multiscan ED volumes showed a good correlation with angio volumes. Mean values were 90.8 for Multiscan versus 97.3 ml/m^2 for angiography ($r = 0.89$). However, ES volumes determined by Multiscan were larger than by angio. Mean values were 51.8 versus 45.9 ml/m^2 ($r = 0.84$). Cumulative data of ES and ED volumes by Multiscan and angio are shown in figure 4. The correlation coefficient of the entire population is 0.94. It is apparent from these results that stroke volume is consistently smaller by Multiscan. As a consequence the LV ejection fraction by Multiscan as compared to angio is also lower. Mean values were 43.2 % versus 52.9 % ($r = 0.58$). In order to test the reliability and reproducibility of this method for LV volume determination, a randomly selected ES and ED polaroid photograph from each of the 17 patients was independently analysed by two different observers. Figure 5 shows the results diagrammatically. A high degree of correlation was found ($r = 0.96$) between the 34 observations and the individual variations were rather small.

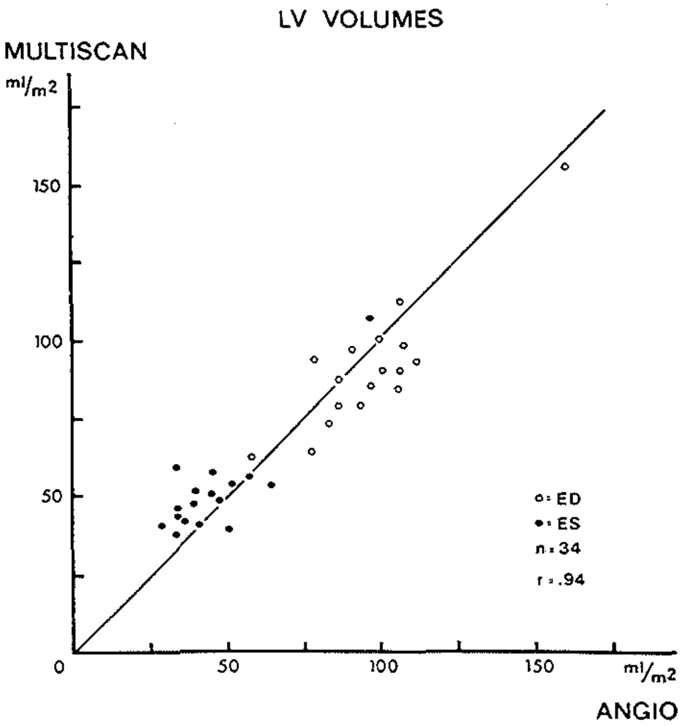


Fig. 4. — This diagram shows a comparison of the cumulative results of end-systolic (ES) and end-diastolic (ED) volumes by Multiscan versus angiography. The correlation coefficient is 0.94 (34 observations).

Discussion

The capabilities of diagnostic ultrasound are expanded by instantaneous two-dimensional moving cross sections of the heart, because all its structures are visualized in a manner familiar to those involved in diagnostic cardiology. A general qualitative assessment of LV function can be made immediately from the display as information about cardiac size, shape and wall motion is immediately available. The sagittal long axis cross section shows the IVS and the LVPW and during transverse scanning along the long axis, large sections of the LV become accessible for study. Regional akinesis, hypokinesis or dyskinesis can thus be recognized. The motion of these areas has to be compared to the normal or exaggerated contraction of the rest of the LV. While the most unique application of the system is the study of the dynamics

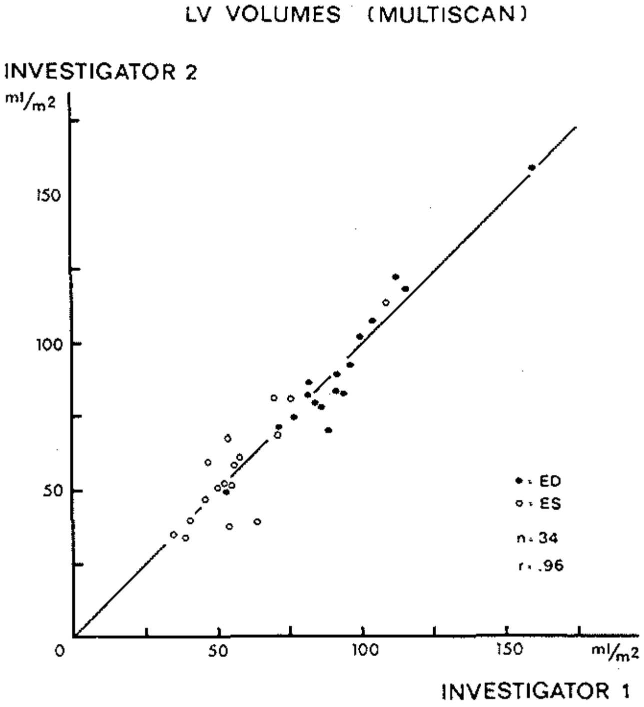


Fig. 5. — To test reliability and reproducibility of the Multiscan for left ventricular calculation, randomly selected end-systolic (ES) and end-diastolic (ED) frames were independently analysed by two independent investigators. A good correlation was found (r = 0.96).

of cardiac contraction and valve motion, it allows also quantitative measurements of cardiac dimensions and LV volumes. Despite the excellent correlations between echo and angio volumes found in studies using the single element echocardiography techniques there are some assumptions to be made [7, 10, 19-21]. Indeed, to calculate the volume from echo-determined LV dimensions, one has to assume that the measured dimensions have constant relationships to the axes of the LV at both ES and Ed also that the echo axis truly approximates the angiographic or minor axis of the LV and that it is half as long as the long axis. This is not true for dilated ventricles and patients with segmental abnormalities of contraction due to coronary artery disease [11, 22, 26]. The Multiscan system may offer here a solution since the angiographic formule proposed by Greene et al. [13] — correcting for variations in geometry — can ba applied. This method is theoretically applicable to ventricles of all sizes and shapes. The initial results of studies in these 17 patients are encouraging. ED volumes calculated from Multiscan frames agree well with angio calculated volumes. There is however a systematic over-estimation of the Multiscan ES volumes as compared to the angio ES volumes, resulting in smaller stroke volumes and an underestimation of the LV ejection fractions. These larger Multiscan ES volumes may be the result of a methodologic difference between ES volumes determined by angio as compared to other techniques such as Fick and indicator dilution techniques [2, 7, 16]. Another possibility is inaccurate timing of ES resulting in more than the true minimum volume. The present series however is too small to draw definitive conclusions or to compare conclusively these preliminary results to those obtained from single element studies. It is expected that both single and multiple element echocardiography will give comparable results for ED volumes. Differences will particularly be noticed for ES volumes in cases with abnormal sized ventricles as a result of segmental myocardial disease.

Nevertheless it appears from these preliminary results that qualitative analysis of the overall LV function is possible and that quantitative measurements can be made in a non-invasive manner with an unlimited frequency. Multiscan echocardiography opens a new area for clinical investigation as well as for teaching and training.

SUMMARY

A multi-element ultrasound system has been developed to provide instantaneous two-dimensional cross-sectional images of the heart in motion. The system expands the capabilities of conventional diagnostic echocardiography by providing unique information regarding the anatomy, the relationship of specific structures and their function. The system should also allow true dimensional measurements of cardiac chambers and great vessels. A systematic technique for clinical studies has been evolved and initial results indicate that records of satisfactory quality can be obtained in most patients. The Multiscan system appears to be of considerable promise for non-invasive studies of the heart.

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CHAPTER 9

LIMITATIONS OF QUANTITATIVE DETERMINATION OF LEFT VENTRICULAR VOLUME BY MULTISCAN ECHOCARDIOGRAPHY

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It has been shown that Multiscan Echocardiography (ME) offers unique possibilities for qualitative assessment of left ventricular (LV) size, shape and dynamic geometry. From the long axis cross-section of the LV, quantitative measurements of volumes with the area-length method appear a logical consequence.
End-diastolic and end-systolic LV volumes calculated from ME LV cross-sections and from quantitative single plane angio were compared in 50 patients (r=0.61, 0.74 respectively). The reasons for this unsatisfactory correlation have been studied and limitations applying to two-dimensional systems analyzed. These include: (1) the angular dependence of reflectivity (poor apical visualisation); (2) the limited dynamic range of oscilloscope display; (3) the limited resolution resulting in erroneous display of structures off the mean axis. Although the physical principle behind this beam width effect is the same for single element (SE) as ME, the appearance on the display is different. "Spurious echoes" of structures occur in SE whereas a "verticalization effect" of structures takes place in ME. This effect can not only introduce interpretation errors but is especially cumbersome for detection of the endocardium. Until better resolution and new display techniques are available, these form limitations of the technique.

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Resolution Problems in Echocardiology: a Source of Interpretation Errors

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Resolution is the ability of the echocardiographic system to distinguish closely lying structures. This is usually defined in two directions: laterally (lateral resolution) and in depth (axial resolution). With use of short ultrasonic pulses, axial resolution is not a major problem. By far the more important problem is the limited lateral resolution that results from the finite beam width of current ultrasonic devices. This results in the display of echoes that originate from off-axis structures. How these off-axis or "spurious echoes" affect the display is a function of the way the echographic information is handled.

In conventional M-mode tracings, spurious echoes are displayed at a site where there is no directly corresponding anatomic structure, whereas with two-dimensional imaging, these echoes may result in important distortions of structures. The underlying principles are illustrated by a clinical experiment wherein the ball of a Starr-Edwards mitral valve prosthesis serves as a target of known shape and dimensions. These data are used to elucidate some of the problems and potential errors encountered in the interpretation of clinical M-mode recordings of the aorta, mitral valve and the left ventricular endocardium as well as their cross-sectional analysis. They also explain the present limitations of quantification of left ventricular performance from cross-sectional images.

One difficulty in the earliest efforts to develop echocardiography as a diagnostic tool was the identification of anatomic structures since the records lacked familiar landmarks. Through the careful anatomic and physiologic studies of Edler et al.,[1] subsequently confirmed and extended by investigators using intracardiac ultrasonic indicators,[2-4] these problems were solved so that most cardiac structures have now been "mapped."

Another important advance was the incorporation into the systems of sensitive strip chart recorders by which M-mode sector scans could be made.[5] Identification of cardiac structures became much easier, and the anatomic interrelations of these structures could be demonstrated with confidence. More recently, two-dimensional ultrasonic systems have been developed to overcome the fact that the M-mode display has no simple, easily understandable relation to the true cardiac anatomy. A variety of technical approaches have now resulted in systems that represent a cardiac cross section in an image not unlike that obtained with cineangiocardiography.[6-12]

Although the origin of most echoes can now reliably be identified by single- or two-dimensional systems alone or in combination, problems in interpretation have arisen because some echoes do not relate directly to a specific cardiac structure. These echoes, referred to as "spurious echoes" in this study, result largely from the limited lateral resolution of ultrasonic systems currently in use. Since ultrasonic energy cannot be accurately focused, and in fact spreads out over a fi-

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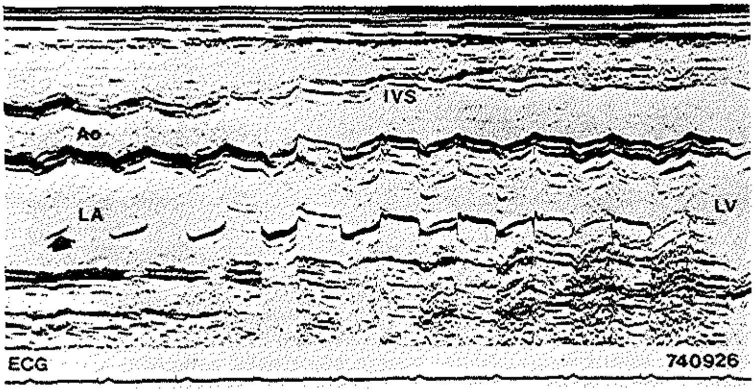


FIGURE 1. M-mode sector scan from aorta (Ao) toward the left ventricle (LV) in a patient with a Starr-Edwards mitral valve prosthesis (type 6310-3u). The tracing was obtained with an Aerotech 0.5 inch transducer, focused at 7.5 cm. At left, the posterior ball echo is erroneously displayed in the left atrium (arrow) although the ball remains in its cage in the left ventricle. ECG = electrocardiogram; IVS = interventricular septum; LA = left atrium.

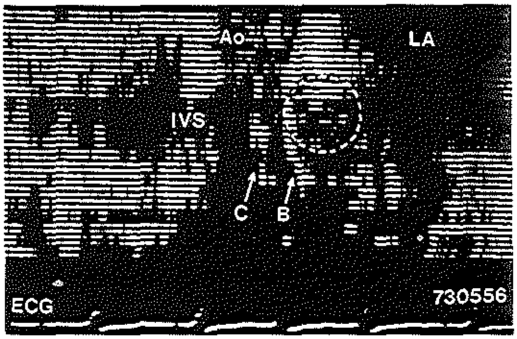


FIGURE 2. A sagittal cross section following the long axis of the heart in a patient with a Starr-Edwards mitral valve prosthesis in place. The true cross section of the ball (type 6310-3M) is outlined. The echo return from the anterior surface of the ball is distorted to a crescent-like pattern (B). Note also the similar distortion pattern of the cage (C) of the prosthesis. Abbreviations as in Figure 1.

nite angle, some echoes appear as if they are from structures in the central beam whereas in fact they are echoes from structures off the central axis. Although this effect has been recognized by physicists,[13,14] clinicians have scarcely paid attention to it[15] and often are not even aware of it although it may lead to misinterpretation of clinical tracings and cross-sectional images. It is the aim of this study to clarify some of these problems and to identify the clinical errors that may result. Knowledge of these factors may aid in understanding some of the difficulties encountered in quantitative measurement of cross-sectional images[16] and may improve the accuracy of left ventricular dimensional measurements in M-mode recordings.

Observations

A Clinical Experiment

To test whether the true location and shape of a cardiac structure are accurately represented in the resulting echographic display, it would be helpful to study a target whose shape is known beforehand. The ball of a Starr-Edwards mitral valve prosthesis provides such a clinical experiment. In this situation the ultrasonic beam scatters in biologic tissues before hitting the target. The intensities used (affecting the beam width) and the gain settings (affecting the axial resolution)[14] are also comparable to those of the average clinical situation. Echographic motion patterns of Starr-Edwards ball and cage valves have been analyzed with use of simultaneously recorded cinefluorography[17] and electromechanical events,[18,19] so that identification of specific structures is possible.

One-dimensional display: An M-mode sector scan obtained from a patient with a Starr-Edwards prosthesis in the mitral position is shown in Figure 1. At left, the ultrasonic beam is directed through the aorta and the left atrium. There should be no evidence of the ball, since it is in its cage in the left ventricle. However, in the tracing it also appears to be in the left atrium. Echoes of the ball extend toward the apex of the left ventricle as well, and remain visible throughout the complete sector scan from the aorta toward the apex. The conclusion must be that echoes are shown at a site where there is no corresponding structure.

Two-dimensional display: In Figure 2, a sagittal cross section through the heart at end-systole is shown. It was obtained with use of a multicrystal ultrasonic system from a patient with a Starr-Edwards mitral valve prosthesis.[9,14,20] The true cross section of the ball is sketched. From it one can see at once that the echo return is badly distorted, providing a poor relation between the true spherical shape of the target and the crescent-like pattern seen in the display (B). It is evident that important distortions occur in the two-dimensional images.

Explanation of these spurious echoes: To explain these spurious echoes, let us consider the straightforward situation in which a single crystal emits an ideal "pencil-like" beam (Fig. 3A) that is aimed at a point parallel to a spherical target. Obviously this beam will miss the target completely so that no echo will be seen in the display. Unfortunately, the ultrasonic energy is not concentrated along a single axis but spreads out over a very finite angle. In Figure 3B the same crystal is shown, emitting its real beam. The main beam passes the target without evoking echoes, but that part of the energy that is deflected from the main axis does strike the target. The echo now displayed would be interpreted as an echo returning along that main axis when in fact it is not. The diagram demonstrates how even

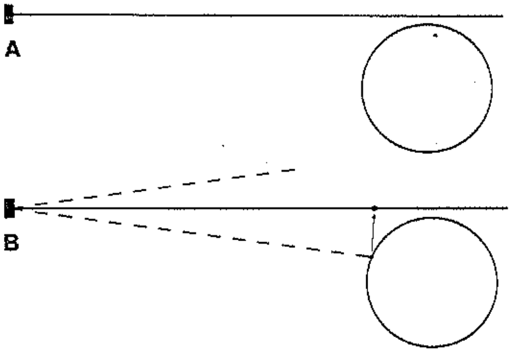


FIGURE 3. Diagrams demonstrating how spurious echoes result from a spherical target when a single element transducer is used (see text).

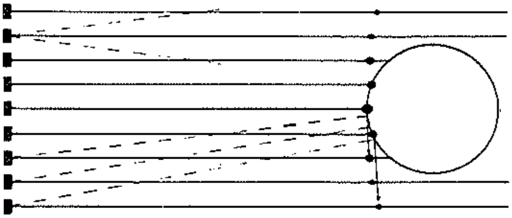


FIGURE 4. Diagram demonstrating how a "crescent-like" pattern of echoes results from a spherical target or ball when a multicrystal system is used (see text).

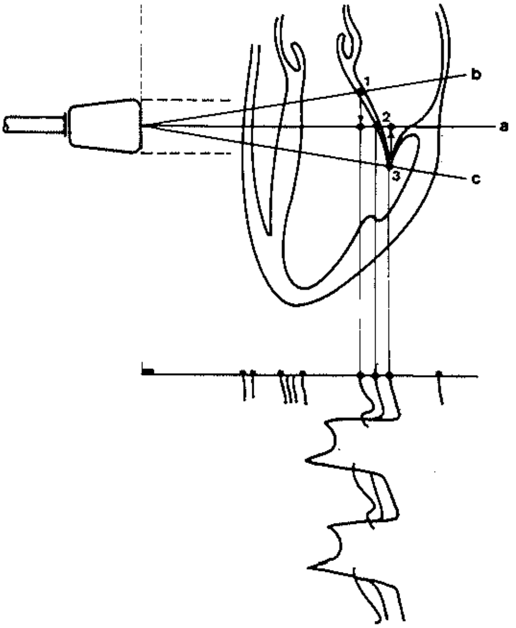


FIGURE 5. Diagram of a saggital cardiac cross section with a single element transducer in place to record the anterior mitral valve leaflet. The main beam (a) passes through the valve at position 2. However, because of the finite beam width, part of the energy along directions b and c will also encounter the valve at positions 1 and 3. Thus, some parts of the valve that are side by side will be displayed behind each other, leading to parallel moving echoes in the resulting M-mode display shown below.

with the use of a focused single element, erroneous echoes can be obtained (Fig. 1).

In the case of a multicrystal display the same problem is compounded. Thus, echoes returning from targets on the ball off the central axis (that is, display axis) together constitute a crescent-like echo pattern. The result is a completely erroneous display of the true (spherical) shape, as shown diagrammatically in Figure 4 and demonstrated by the clinical case in Figure 2. This is an extreme example since a ball valve is a very strong reflector with specular reflectivity characteristics. Its analog is unlikely in biologic tissues or structures. Nevertheless, it serves to identify a fundamental drawback not only of two-dimensional displays, but also of all ultrasonic systems.

Spurious Echoes of the Mitral Valve and Aorta

One-dimensional display: With an ideal pencil-like ultrasonic beam, the recorded echoes should represent the correct position of each reflecting structure in the beam axis. In Figure 5 this situation is schematically shown for that part of the reflecting anterior mitral valve leaflet through which the ideal beam passes vertically. Because of the imperfections in the beam width, parts of the mitral valve "off axis" will also be "seen" by the transducer. Although the parts of the mitral valve labeled 1, 2 and 3 are struck in a predominantly vertical manner, the resulting display shows them behind each other in the form of multiple parallel echoes.

This phenomenon is demonstrated clinically by the M-mode, sector scan (Fig. 6) from a patient with an atrial septal defect of the secundum type and a large left to right shunt (2.5:1). The mitral valve was found to be completely normal during open heart surgery, although the multiple mitral valve echoes during systole could suggest mitral valve disease. Similarly, echoes from the root of the aorta indicated by arrow A are picked up while the transducer is aimed at the mitral valve. The off-axis origin from the posterior aortic wall is inferred from the shape of the echo and from its timing within the cardiac cycle, which is similar to that of echoes obtained when the main beam is aimed directly at the aorta.

Two-dimensional display: In a two-dimensional display a rather different appearance results from these multiple echoes from the anterior mitral valve. Whereas with a single element, multiple adjacent parts of the same valve leaflet are displayed as if they were behind each other (Fig. 5), a "verticalization-effect" occurs in cross-sectional images. This is diagrammatically shown for a multicrystal system in Figure 7. A sagittal cross section obtained from a normal person will look like the photograph in Figure 8, in which the shape of the mitral valve is distorted and much thicker than the thin structure it actually is. This occurs as there are several vertically superimposed spurious echoes appearing in the display. These same problems affect the display of the aortic root and, as a consequence, determination of the long axis of the left ventricle. Indeed, it is difficult to assess to what extent spurious echoes of the root of the aorta extend into the left ventricular cavity. This obviously causes serious limitations to quantitative studies of ventricular dimensions in the determination of the long axis.

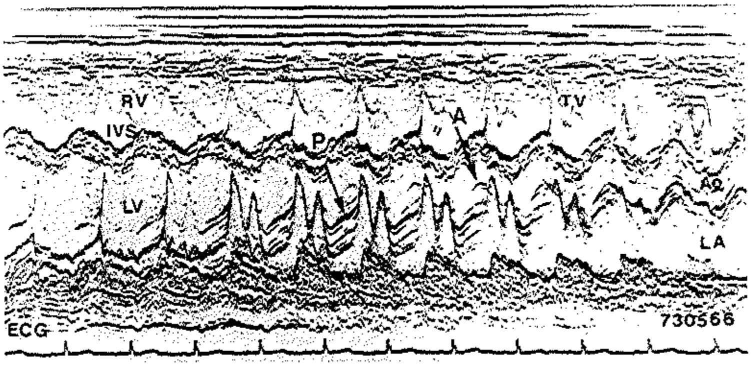


FIGURE 6. Spurious echoes from mitral valve and aorta. M-mode sector scan from the left ventricle toward the aorta obtained from a patient with an atrial septum defect of the secundum type. An Aerotech 0.5 inch transducer focused at 7.5 cm was used. There are spurious echoes of the posterior aortic wall (arrow A) at the level of the mitral valve and multiple echoes of the anterior mitral valve leaflet (arrow P). The valve was found to be normal at operation. RV = right ventricle; TV = anterior tricuspid valve; other abbreviations as in Figure 1.

Erroneous Echoes of the Endocardium

The proper identification of the left ventricular endocardial echoes becomes more important when attempting to assess the function of the left ventricle from its moving dimensions. The same distortions occur but, because of the complicated contraction sequence and the changing geometric structure of the left ventricular cavity, some specific problems result, especially for left ventricular cross-sectional imaging.

One-dimensional display: When studying left ventricular dimensions in M-mode recordings, one may see misleading echoes of the endocardium. This is demonstrated by the M-mode recording of the standard left ventricular dimension of Figure 9 obtained from a normal subject. With an "0.5" inch transducer "focused at 7.5 cm," the endocardial echo is recorded at a low gain. When the gain is increased, multiple parallel moving echoes that probably originate off the main axis are picked up during diastole (arrow). Since the gain can be easily modulated and the system has high resolution, identification of the true endocardial echo is easily accomplished. Note also in Figure 9 that these echoes merge during systole. This might be explained by the angle of inclination of the endocardium toward the ultrasonic beam, which becomes more "favorable," causing the spurious echoes to occur closer to the true endocardial echo. These features are demonstrated for a multicrystal array in Figure 10 but apply for each single element as well.

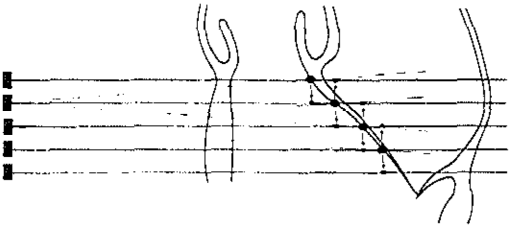


FIGURE 7. The multiplication of the erroneous echoes from each single crystal as demonstrated in Figure 5 results in a "verticalization pattern" of the mitral valve when a multicrystal system is used.

Two-dimensional display: Spurious echoes particularly affect the display in systems using a multicrystal array. The explanation is diagrammatically represented in Figure 10. The strength of the echoes is related to the angle at which the ultrasonic beam hits the target.[13] If the target is perpendicular to the beam, that is, "favorable," the reflected echo is strong and both true and phantom echoes fall together. When the same target is inclined, less energy will return to the crystal and the echoes become weaker. Furthermore, the higher the angle of inclination of the target to the direction of the beam, the further the phantom echoes are displayed from the true endocardial surface. Thus, the amount of distortion increases with the inclina-

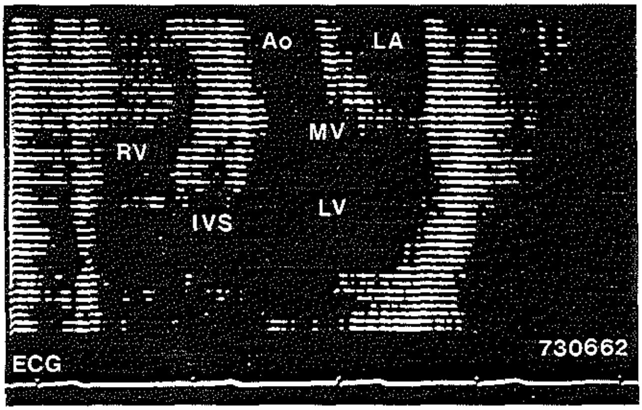


FIGURE 8. Distortion of mitral valve echoes with a multiscan. Sagittal cardiac cross section following the long axis of the left ventricle. Note the peculiar display of the mitral valve (MV) which is seen as multiple vertical echoes (diagrammatically shown in Figure 7). RV = right ventricle; other abbreviations as in Figure 1.

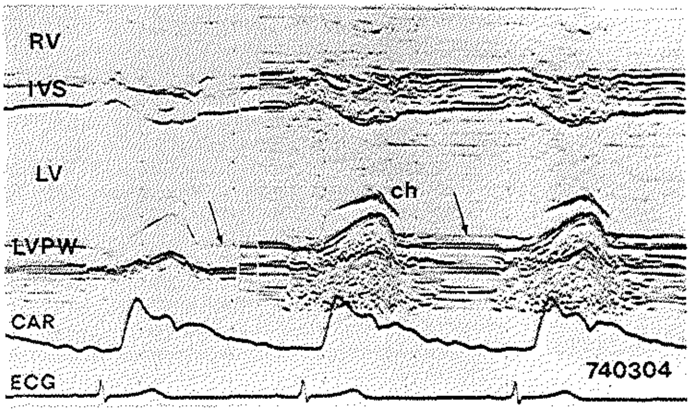


FIGURE 9. Spurious echoes from the endocardium in a standard echocardiogram used for dimensional measurements of the left ventricle (see text). CAR = carotid arterial tracing; ch = chordae tendineae; LVPW = left ventricular posterior wall; RV = right ventricle; other abbreviations as in Figure 1.

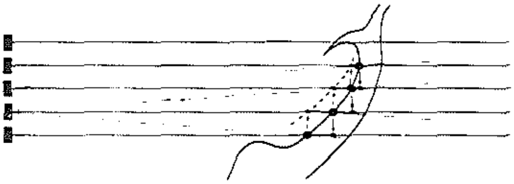


FIGURE 10. Schematic drawing of the left ventricular posterior wall. Targets from the endocardium are distorted in the vertical direction. This effect is more pronounced when the inclination of the target to the ultrasonic beam increases until at a certain angle, there is no more echographic return. This results in poor visualization of the apex. The internal shape of the left ventricle is distorted because the true endocardial surface **(solid line)** is erroneously displayed by the **dotted line.**

tion until at a certain angle no echoes return to the crystal, thus explaining, in part, the poor visualization of the apex.

These problems are demonstrated in the cross sections, in Figure 11, obtained from a normal subject, in which the endocardial surface is represented by vertical lines (verticalization effect). The effect is most marked at the left side of the septum. Moreover, the apex is poorly defined. The often encountered "drop-out" phenomenon (the sudden loss of echoes from an anatomic structure in the ultrasonic beam) is similarly explained. For example, when the shape of the left ventricular chamber is irregular, parts of the septum or the posterior wall, or both, may have an unfavorable angulation to the ultrasonic beam, resulting in poor reception of echoes and thus "missing" parts of these structures in the display (Fig. 8).

Discussion

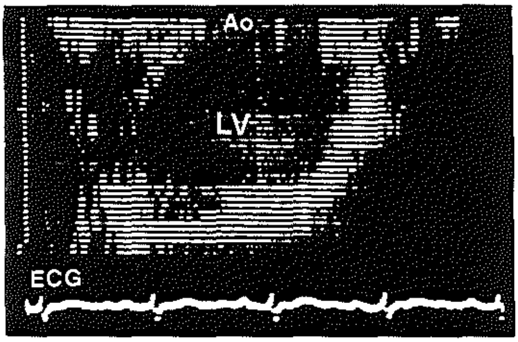
Poor lateral resolution of echoes (spurious echoes): By far the most serious limitation of currently used pulse-echo systems is the poor lateral resolution described in this paper. Because ultrasonic energy cannot be focused over the entire depth range of the beam there will always be echoes generated and received from structures located away from the main or display axis. This effect depends also on sonic frequency and element size. Although this problem can be relatively reduced for structures at a given depth by the use of a focused transducer, it is still present, as demonstrated herein.

"Dropout" of echoes: Beam width is only a relative indication since strong reflectors in a given direction will be "seen," whereas weak reflectors will not. Thus, echo amplitudes from reflecting structures may vary widely, again depending on several physical factors. These are the attenuation of sonic energy with propagated distance due to absorption in the tissues and differences in acoustic impedance and angle of incidence of the ultrasonic beam. Furthermore, currently used systems can display echoes only within a selected limited range of amplitudes. As a direct consequence of all these factors, anatomic structures may not be seen in the display ("dropouts") and a false positive diagnosis of a ventricular septal defect might be made, as demonstrated in Figure 8. On the other hand, the beam width limits the smallest size of a septal defect when it is ideally perpendicular to the direction of the sonic beam. Thus, a false negative diagnosis will often be made. In contrast to suggestions made by others,[21] we have never been able to visualize reliably ventricular septal defects proved by cardiac catheterization data.

Overlapping of echoes: On the other hand, the visible echograms may show too much. This is due not only to the lateral resolution but also to the echo length, which influences the image (axial resolution). With too high gain settings, there will be several overlapping echoes and it then becomes difficult to identify and locate a specific interface or structure.[14] This principle has resulted in specific examination techniques in particular for mitral stenosis, pericardial effusion and atrial myxoma where proper gain settings can avoid false positive or negative diagnosis.[5,15,22,23]

Errors in interpretation of mitral valve motion: A common problem of interpretation resulting from the limited lateral resolution in M-mode recordings is the appearance of multiple mitral valve echoes in systole, which is a well known normal finding (Fig. 6). However, we are aware of several cases in which mitral incompetence was assessed because the finding was interpreted as separation of the leaflets. Distortions of the mitral valve are introduced in the two-

END-DIASTOLE



END-SYSTOLE

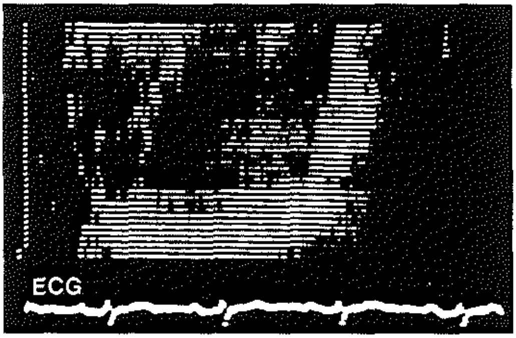


FIGURE 11. End-diastolic **(top)** and end-systolic **(bottom)** (see right edge of the electrocardiogram) cross sections obtained from a patient with minimal heart disease as used for calculation of left ventricular volumes. The outer contour of the left ventricle is composed of vertical lines (most apparent at the septum) which hampers the correct identification of the endocardium. Note also the poor visualization of the apex and the difficulty to locate the aortic and mitral valve plane. All these factors limit the possibility to exactly define the long axis and to outline the surface area of the left ventricle and hence volume calculations. Abbreviations as in Figure 1.

dimensional displays. This can be clearly demonstrated for the mitral valve when a multicrystal array is used (Fig. 8), but the distortions are also seen in the cross sections obtained with a mechanical scanner using a focused transducer.[10,11] Spurious echoes of the posterior aortic wall recorded with the mitral valve echogram could suggest systolic anterior movement of the valve. Here, a false positive diagnosis of idiopathic hypertrophic subaortic stenosis could be made by the inexperienced examiner.[24]

Problems of interpretation in measuring left ventricular dimensions and volumes: Another related problem arises in the measurement of internal left ventricular dimensions. It is clear that the location of an interface in the display is determined by the location of the first (onset) rather than the last deflection produced by the echo. When higher gain settings (often needed because the endocardium-blood interface is a poor reflector) are used, the length of the echoes increases and thus endocardial echo of the left side of the interventricular septum is extended into the left ventricular cavity. Then when the internal left ventricular dimension is measured, a 5 percent error is easily introduced especially on polaroid photographs, where the definition of echoes is limited as a result of the spot size on the screen. This results in an error of 15 percent when the cube law is used to calculate the estimated volumes.[25] Therefore, one should always measure dimensions from the onset of the echoes in M-mode recordings.

Spurious echoes and related distortions seriously limit visualization of the true internal size and shape of the left ventricle, which has important clinical implications. Indeed, since complete visualization of the shape of the left ventricle is a unique feature of two-dimensional systems, cardiologists are tempted to analyze these left ventricular cross sections quantitatively in very much the same manner as angiocardiograms.[26-28] However, the poor correlation coefficient and the large standard errors found in a series of 50 consecutive patients whose left ventricular volumes were calculated from angiocardiograms and ultrasonic cross-sectional images by means of the area-length formula[29] indicate that no reliable relation exists.[16] The reason for this poor correlation is clear from the earlier discussion since there may be many spurious echoes of the aortic root, mitral valve or endocardium in a cross-sectional display. Other pitfalls are incomplete visualization of the apex and, often, missing segments in the record. Accurate measurements of the long axis and correct tracing of the inner contour of the left ventricle are crucial for volume calculations. Errors in these measurements are further compounded when formulas for volume calculations are used. Viewing a moving image on a screen alleviates some of these problems since the human capability for pattern recognition is unsurpassed. This problem has its analog in the analysis of still frames from a moving picture obtained with cineangiocardiography. To use the entire series of moving images would require special processing techniques. These are at present under development in our laboratory and elsewhere, but their efficacy is as yet unproved.

Problems of interpretation in identifying endocardial echoes: Endocardial M-mode recordings also suffer from the same lateral resolution problem but, although multiple parallel echoes are often recorded (Fig. 9), identification of the central endocardial echo is much easier than in a two-dimensional display, particularly when high resolution systems are used. Indeed, because the "true" endocardial echo has the greatest intensity, it is the last to disappear when gain settings are gradually decreased. With a less flexible or less sensitive system—for example, those with direct photographs—all these echoes may be seen together as a single wide echo. Consequently, measurement errors are readily made, as with the single scan. However, because of the advanced systems now used for M-mode recordings, and the availability of a convenient tracing, measurements are more reliable now than formerly.

It has been suggested that the steepest moving echo of the left ventricular posterior wall represents the endocardium. It often makes contact with the posterior chordal echoes during systole in smaller-sized ventricles,[4,20] and spurious echoes of the endocardium could thus be mistaken for chordal echoes. However, careful inspection of the multiple echoes from the region of the endocardium in Figure 9, reveals that they all have the same motion pattern. This is unlikely for a chordal echo since the latter should be influenced to some extent by the mitral valve motion in diastole and therefore show a different pattern. Furthermore, the greater intensity of the endocardium during systole may suggest that its angle of inclination toward the ultrasonic beam becomes more "favorable." This also explains why the spurious echoes would merge with the true endocardial echo. A chordal origin of some of these echoes has been suggested by the observation that, when the left ventricular cavity was outlined exactly through injection of ultrasonic markers,[4] the echoes fell within the cavity; however, this observation does not disprove our alternative explanation.

In addition to recognizing the factors enumerated, investigators should be aware that quantitative analysis of these "still" frame images requires considerable knowledge and experience. A thorough knowledge of the basic physics of echocardiographic techniques, their pitfalls and limitations, as well as a clear understanding of cardiac anatomy, pathology and physiology are necessary. Thoughtless application of a new technique leads to misinterpretation and may actually hamper its development as a diagnostic tool.[30] The history of quantitative angiocardiography has an interesting and perhaps relevant lesson for echocardiographers: Although analysis of video lines rather than the complete two-dimensional picture is only now being proposed as a more accurate process for quantitating angiographic images,[31,32] the technique of echocardiography started with analysis of a single dimension.

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CHAPTER 11

REAL TIME CROSS-SECTIONAL CONTRAST ECHOCARDIOGRAPHY FOR THE DETECTION OF INTRACARDIAC RIGHT TO LEFT SHUNTS

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11.1 SUMMARY

The usefulness of performing real time cross-sectional echo contrast studies, using peripheral venous injections of dextrose 5% in water, for the detection and localization of atrial and ventricular right to left shunts was evaluated in 69 adult patients. 36 patients without a shunt by oxymetry served as controls (group I). Echo contrast could not be detected in the left-sided cardiac cavities in any of the control patients. Based on their catheterization data, 20 patients had a shunt at atrial level (group I) and 13 patients a ventricular septal defect (group II).

In 11 of the 15 patients with an uncomplicated atrial septal defect of the secundum type, echo contrast appeared at the left side of the heart and this small right to left shunting occurred in systole.Left-sided echo contrast was demonstrated in the 5 patients in whom a bidirectional atrial shunt was found by oxymetry.

Of the 13 patients with a ventricular septal defect, 7 had a ratio of right to left ventricular pressure exceeding 45% and early diastolic right to left shunting of echo contrast was observed in all. This was not seen in any of the 6 patients with an uncomplicated ventricular septal defect.

It is concluded that diagnostic real time ultrasonic cross-sectional contrast studies using peripheral venous injections of dextrose 5% in water can be performed in adults. The presence and timing of these intracardiac right to left shunts, even when small, are greatly facilitated.

11.2 INTRODUCTION

Gramiak and Shah (1) reported in 1968 that rapid injection of indocyanine green produced a cloud of echoes in the blood which is otherwise echofree. They used this method to identify intracardiac structures and to validate echocardiographic patterns. Subsequent studies showed that any solution rapidly injected into the circulation produces echocardiographic contrast (2). The effect most likely results from the drop in pressure at the catheter tip during injection which allows the gasses dissolved in the blood to escape in the form of miniature bubbles following the Bernouilli principle (3, 4). Other explanations for the phenomenon include turbulence, temperature differences and fluid acoustic impedance differences. These clouds of echoes can be observed downstream from the injection site on and loose their echo producing quality with a single transit through either the pulmonary or the systemic capillary bed. This means that detection of echoes in both the venous and arterial blood pool after peripheral vein injection of a contrast producing agent is always indicative of abnormal shunting. This principle has been used with M-mode echocardiography to study intracardiac shunts, blood flow patterns and pressure-flow relationships (5-13).

We evaluated peripheral injection contrast echocardiography using a real time cross-sectional imaging instrument in patients with and without intracardiac shunts to determine the feasibility and clinical usefulness of this technique in detecting and localizing shunting blood flow.

11.3 MATERIALS AND METHODS

11.3.1 Patient population

Real time cross-sectional contrast studies with peripheral vein injection were performed in 69 patients, 47 males and

22 females, ages ranging from 17 to 64 years. All were referred to the Thoraxcenter for cardiac evaluation and underwent a complete hemodynamic and angiographic study. They were divided into 3 main groups.

Group I:
36 patients in whom no intracardiac shunt was demonstrated during catheterization and they served as controls.

Group II:
Twenty patients with an atrial septal defect; 15 of the secundum type, 2 of the primum type and 3 associated with Ebstein's anomaly (Table I).

Group III:
Consisted of 13 patients with a ventricular septal defect; 6 with an isolated defect (Table II), 2 with a Fallot's tetralogy, 1 with pulmonary atresia, 1 with truncus arteriosus, 1 with pulmonary hypertension and 2 with valvular pulmonary stenosis (Table III).

The intracardiac shunt ratios of the patients in both groups were derived from standard formulas using values for systemic and pulmonary arterial and mixed venous oxygen saturations: the latter was calculated from superior and inferior vena cava oxygen contents (14). A summary of these data is presented in tables I, II en III.

11.3.2 Instrumentation

Real time cross-sectional ultrasonic studies were performed using a dynamically focussed multiscan system (15). The linear array transducer consists of 51 elements of which subarrays of 12 elements are used for both transmission and reception.

Table I Pertinent Data of patients with atrial septal defect

Patient	Age (yrs) Sex Type of ASD	Aortic Saturation (%)	QP/QS	RVSP (mm Hg)	LVSP (mm Hg)	RVID (mm) M Mode	Paradoxical Septal Motion M Mode	Left-sided Echo Contrast
1 JC	19 female/secundum	98	4	47	158	40	yes	yes
2 ABB	64 female/secundum	90	2.1	112	144	50	no	yes
3 IVE	29 male/primum	89	4	49	165	33	no	yes
4 KH	24 female/secundum	96	3.8	42	156	30	no	yes
5 F KU	34 female/secundum	95	3.8	42	131	20	no	yes
6 DL	29 male/secundum	95	3.8	35	124	40	yes	yes
7 JMG	17 female/primum	97	3.1	32	85	37	no	yes
8 PM	20 female/secundum	96	2.5	56	136	40	yes	yes
9 HP	19 female/secundum	97	4.1	38	144	40	yes	yes
10 AP	39 male/secundum	96	2.8	34	143	35	yes	yes
11 MR	31 female/Ebstein	91	1.6	22	118	70	yes	yes
12 JB	27 male/secundum	95	3.2	88	100	30	yes	yes

Tabel I (continued)

Patient	Age (yrs) Sex Type of ASD	Aortic Saturation (%)	QP/QS	RVSP (mm Hg)	LVSP (mm Hg)	RVID (mm) M Mode	Paradoxical Septal Motion M Mode	Left-sided Echo Contrast
13 JR	21 male/secundum	97	3.8	34	104	40	yes	yes
14 YV	34 female/secundum	96	1.3	22	139	28	no	yes
15 YR	16 female/Ebstein	92	2.3	34	122	30	no	yes
16 VW	22 female/Ebstein	84	1.45	18	114	70	yes	yes
17 MZ	29 male/secundum	95	A +	31	129	40	no	no
18 CR	44 male/secundum	95	3.4	29	171	30	yes	no
19 JR	21 female/secundum	96	2.4	29	120	36	no	no
20 BV	34 male/secundum	95	4.5	28	128	45	yes	no

Abbreviations: QP/QS: pulmonary-to-systemic flow ratio; RVSP: right ventricular systolic pressure;
LVSP: left ventricular systolic pressure; RVID: right ventricular internal diameter.
A + : angiographically proven.

Table II PERTINENT DATA OF PATIENTS WITH ISOLATED VENTRICULAR SEPTAL DEFECT

Patients	Age (yrs) Sex	Aortic Saturation (%)	QP/QS	RVSP (mm Hg)	LVSP (mm Hg)	RVID (mm) M Mode	Paradoxical Septal Motion M Mode	Left-sided Echo Contrast
1 DC	24 male	97	1.5	29	125	20	no	no
2 JVB	19 female	97	1.5	36	132	15	no	no
3 CG	25 male	97	1.7	29	126	25	no	no
4 VD	19 male	96	1.6	25	140	25	no	no
5 MVE	40 female	97	2	34	114	25	no	no
6 EW	30 female	98	1.5	24	140	20	no	no

Abbreviations: QP/QS: pulmonary-to-systemic flow ratio; RVPS: right ventricular systolic pressure; LVPS: left ventricular systolic pressure; RVID: right ventricular internal diameter.

Table III PERTINENT DATA OF PATIENTS WITH VENTRICULAR SEPTAL DEFECT AND ASSOSCIATED PATHOLOGY

Patient	Age (yrs) Sex	Associated Pathology	Aortic Saturation (%)	$\frac{PBF}{EPBF}$	$\frac{SBF}{EPBF}$	RVPS (mmHg)	LVPS (mm Hg)	RVID (mm) M Mode	Paradoxical Septal Motion M Mode	Left-sided Echo Contrast
1 JVE	29 female	pulmonary hypertension	86	1.65	1.57	130	130	--	--	yes
2 EWR	21 female	operated Fallot with residual shunt	96	3.75	--	51	100	28	no	yes
3 IS	19 female	valvular pulmonary stenosis	97	1.5	--	120	124	22	no	yes
4 AHV	51 female	valvular pulmonary stenosis	90	1.43	1.36	110	124	30	no	yes
5 AK	22 male	truncus arteriosus	88	--	--	110	110	37	no	yes
6 AJV	26 female	pulmonary atresia	78.5	1.5	1.62	145	145	10	no	yes
7 H	40 male	Fallot, Potts procedure	90	1.4	1.6	130	140	18	no	yes

Abbreviations: EPBF: effective pulmonary blood flow; PBF: pulmonary blood flow; SBF: systemic blood flow; RVPS: right ventricular systolic pressure; LVPS: left ventricular systolic pressure. RVID: right ventricular internal diameter.

In transmission, an axicon focus is applied. During reception, six adjacent zones are sequentially focussed and adjusted to the depth from where the echoes originate at that particular moment. The operating frequency is 3,12 MHZ; the effective beam width of each sub-array is 2 mm, yielding a good lateral resolution over the entire depth of the explored cross-section. Each frame consists of 40 basic lines and the dimensions of the rectangular cross-sectional image are 8 x 16 cm. The system operates at a rate of 50 frames per second. The ECG is displayed at the bottom of the picture for timing purposes, the right end edge indicating the moment of the frame within the cardiac cycle. Images are recorded on video tape which allows their subsequent analysis in real time, slow motion or stop frame. Individual frames can be photographed using instant Polaroid photography.

11.3.3 Echo contrast procedure

After initial standard M-mode echocardiography and cross-sectional analysis, an 18-gauge teflon venous sheath was inserted into a right antecubital vein. Through this venous route, injections of echo contrast material (10 ml of dextrose 5% in water) were carried out (on average 10 times) whilst cardiac cross-sections were continuously recorded on video tape.

11.3.4 Examination procedure

The cross-sectional contrast studies were performed with the patients in the recumbent or slightly left lateral position. Most attention was given towards visualization of the left ventricular inflow and outflow portions, since if any contrast material would pass to the left-sided cavities, the chance of identifying it would be greatest in these areas (figure 1).

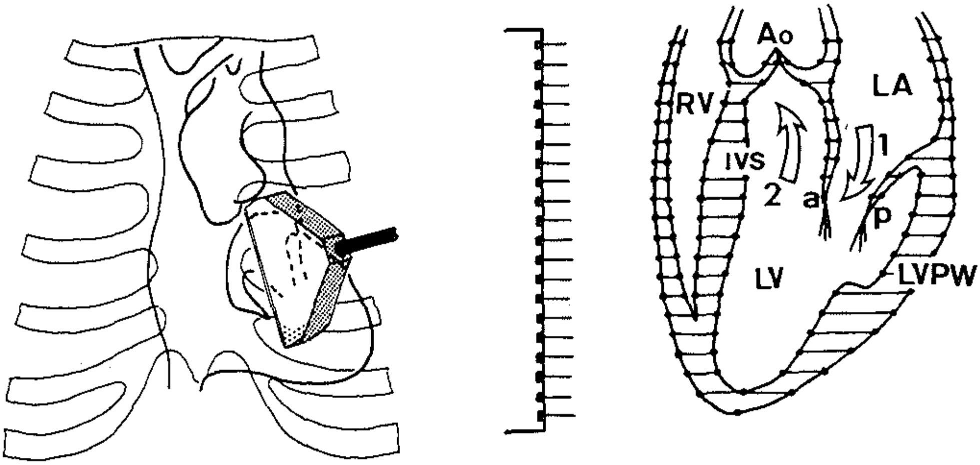

Figure 1.

The left panel shows the transducer in the position on the chest wall which permits visualization of a sagittal cardiac cross-section passing through the long axis of the left ventricle. The right panel is a diagrammatic representation of the visualized cross-section. The arrows indicate the inflow (1) and outflow tracts (2) of the left ventricle. Echo contrast is most likely to be detected in these areas when it passes from the right to the left side of the heart.
Ao: aorta; a and p: anterior and posterior mitral valve leaflets; IVS: interventricular septum; LA: left atrium; PW: left ventricular posterior wall; RV: right ventricle; I: inferior; S: superior.

They are usually best seen in a cross-section following the long axis of the left ventricle (16).
Left sided appearance of echo contrast was considered as positive when contrast echoes appeared in the left atrium, left ventricular inflow and/or outflow tract. To avoid false positive tests as a result of overload effects, great care was taken to use the lowest possible gain settings.

11.4 RESULTS

In the control group of patients without intracardiac shunt (group I), acoustic opacification remained confined to the right ventricular cavity and outflow tract. The right-sided contrast effect cleared rapidly, usually after 2-5 cardiac cycles, except in patients with tricuspid valve incompetence, pulmonary insufficiency or low cardiac output state, where it may be observed for over 30 seconds. Interesting information on right ventricular flow dynamics was obtained in a patient with Björk-Shiley tricuspid valve prothesis. The flow pattern or vortex direction produced by the valve could be easily followed (figure 2).

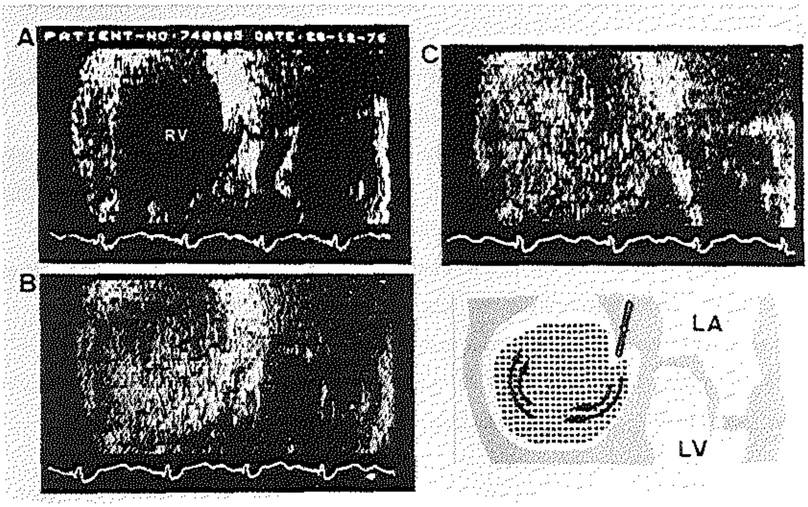

Figure 2.
Cross-sections through the right ventricle (RV) obtained from a patient with a Björk-Shiley tilting disc prothesis in the tricuspid position. After peripheral vein injection of dextrose 5% in water, the RV fills with echo contrast and the flow pattern produced by the valve can be analyzed (frames B and C).

This vortex continued to circulate after cessation of the diastolic filling into the systolic ejection period. This pattern is similar to that observed in in vitro experiments by Wright (17). The findings of the ultrasonic contrast studies in the 20 patients with an atrial septal defect (group II) are given in figure 3.

	AORTIC O_2 SATURATION	
	$>$ 95% N = 15	$<$ 95% N = 5
POSITIVE	11	5
NEGATIVE	4	0

Figure 3.
Left-sided appearance of echo contrast in 20 patients with an atrial septal defect.

Of these, 15 patients had an atrial septal defect of the secundum type and no aortic desaturation was measured by oximetry. However, a systolic right to left passage of echo contrast material was observed in 11 patients (figure 4). A circular echofree space was seen posterior to the atrioventricular groove in one patient with an atrial septal defect.
This structure was proven to be a left superior vena cava by a left arm vein injection (figure 5).
In 3 patients with a negative contrast study the Q_p/Q_s ratio was 2.4, 3.4 and 4.5 respectively. Five patients had in addition to their left to right shunt, a right to left shunt which was demonstrated by oximetry (aortic oxygen saturation of less than 95%). These 5 patients all showed left-sided appearance of echo contrast (figure 6).

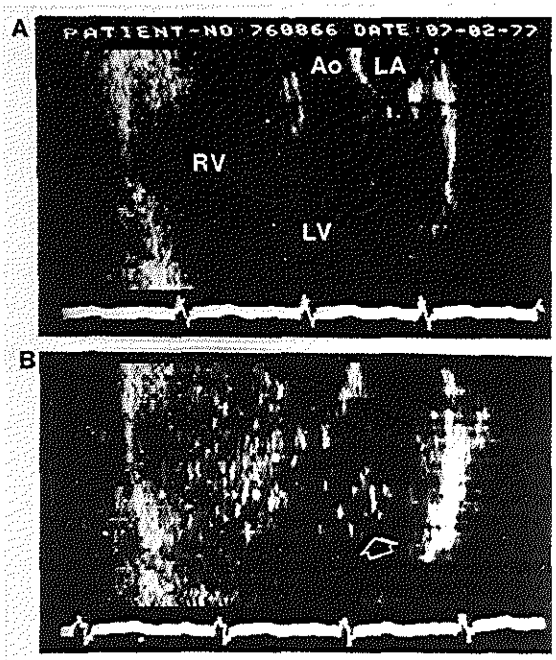

Figure 4.
Long axis cross-sections of a patient with an atrial septal defect of the secundum type. After peripheral vein injection, the echo contrast fills the right ventricular cavity (RV) and appears in the left ventricular inflow tract during diastole (see arrow) indicating a shunt at atrial level. Ao: aorta; LA: left atrium; LV: left ventricle.

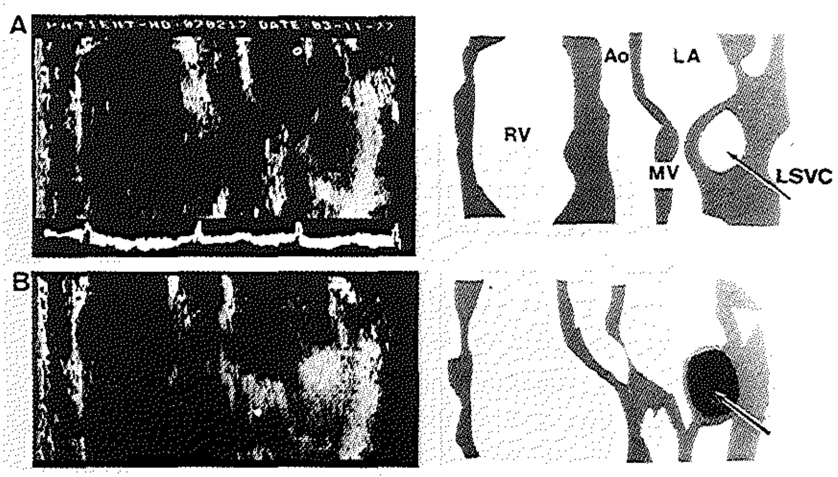

Figure 5.
Long axis cross-sections of a patient with an atrial septal defect of the secundum type and a left superior vena cava (LSVC). After injection of dextrose 5% in water in the antecubital vein of the left arm, the left superior vena cava (or sinus coronarius) is opacified (see arrow - frame B). Ao: aorta; RV: right ventricle; LA: left atrium; MV: mitral valve; LV: left ventricle.

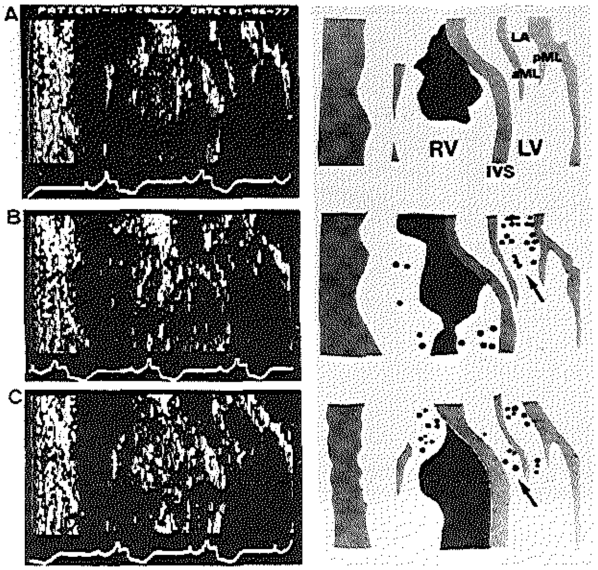

Figure 6.
Sagittal long axis cross-sections obtained from a patient with Ebstein's anomaly and bidirectional shunt at atrial level. On frame A, one sees the ultrasonic contrast filling the dilated right ventricle (RV). On frame B, bright specks of echo contrast which accumulated above the mitral valve in early systole pass into the inflow tract of the left ventricle (LV) in diastole (see arrow). They are detected in the left ventricular outflow tract (LVOT) at the onset of the next ventricular contraction (see arrow - frame C).

In the patients of group III with isolated ventricular septal defect and normal right-sided pressures, the echo contrast remained confined to the right ventricular cavity and outflow tract. Conversely, in all 7 patients with a ratio of right to left ventricular pressure exceeding 45%, an early diastolic passage of echo contrast from within the right ventricle into the left ventricular outflow tract was demonstrated (figures 7 and 8). In these patients, the aortic oxygen saturation was $< 95\%$.

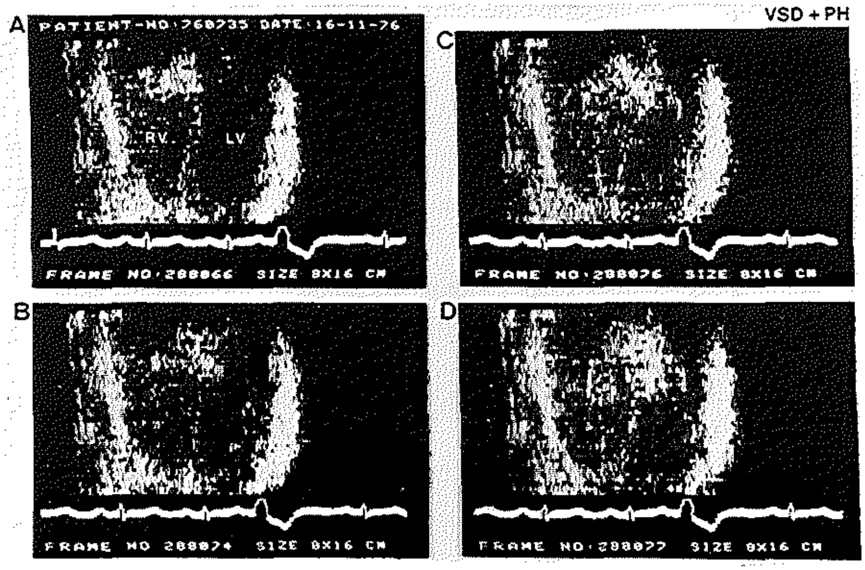

Figure 7. Cross-sections through both the right (RV) and left ventricle (LV) obtained from a patient with large ventricular septal defect, patent ductus arteriosus and Eisenmenger syndrome. Cloud of echoes appears first in the right ventricular cavity (frame A) and then passes into the left ventricle via a ventricular septal defect in the left ventricular outflow tract during early diastole of the next cardiac cycle (frames B-D).

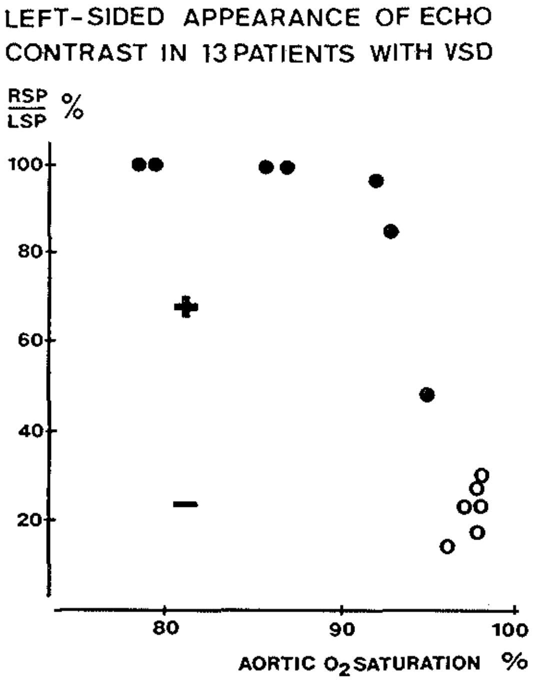

Figure 8.
Positive (+) and negative (-) left-sided appearance of echo contrast in relation to the aortic oxygen saturation and the ratio between right and left ventricular systolic pressure in 13 patients with ventricular septal defect.

11.5 DISCUSSION

Much of the attraction of peripheral vein injection contrast studies results from the potential of studying intracardiac flow dynamics noninvasively and outside the catheterization laboratory (5, 8-10, 13). The initial observations were obtained with single crystal M-mode echocardiography: the ultrasound beam, aimed along one of the standard axes, e.g., through the right ventricular outflow tract, aorta and left atrium is kept immobile throughout the contrast study. The appearance of contrast in any of these cavities and its timing enables the examiner to deduce the presence of an intracardiac shunt and eventually its location. With bidimensional contrast techniques, contrast-filled blood will be seen to flow through the defect when the appropriate cross-sectional plane is selected for investigation.

M-mode echocardiography was found to be of value in the detection of conditions associated with right-sided volume overload (18-20), but its specificity and sensitivity for the diagnosis of an atrial septal defect have been questioned (21). In fact, despite some succesful attempts to visualize the interatrial septum (22) with the M-mode approach, the direct visualization of a defect has been inconsistent. Gated B-scan techniques (23) and real time cross-sectional echocardiography (24, 25), while more attractive methods for the definition of the interatrial septum, sometimes fail to demonstrate a localized gap in the mid-portion of the interatrial septum. "Drop-outs" suggesting a false positive defect diagnosis may also occur.

In other words, structural abnormalities cannot be diagnosed with certainty, unless additional evidence of an abnormal intracardiac flow pattern is obtained. An attractive method for the demonstration of abnormal intracardiac blood flow patterns is offered by the use of ultrasonic contrast agents. Some workers have evaluated the diagnostic value of a negative contrast shadow during diastole in the opacified right atrium at the level of the atrial septal after peripheral vein injection of cardiogreen (24).

Detailed physiological studies with atrial pressure-flow dynamics, angiography and dye dilution curves have consistently demonstrated minor amounts of right to left shunting during early systole in patients with uncomplicated ASD (26, 27). Detection of ultrasonic contrast in the left-sided chambers should therefore provide an argument for the diagnosis of an ASD and was evaluated in this study. Left-sided appearance of echo contrast was seen in 11 of 15 patients with classic ASD and in whom oxymetry did not demonstrate aortic desaturation. The echo contrast method is thus a very sensitive method in demonstrating small right to left shunts and may prove the diagnosis of an atrial septal defect in patients with equivocal clinical and M-mode findings.

A likely explanation for this higher sensitivity is that each microbubble remains a detectable entity whereever it is located in the left atrium, left ventricular inflow or outflow tracts. On the contrary, detection of oxygen depleted blood is dependent on the volume of right to left shunting and also on the positioning of the catheter tip used for blood sampling. In addition, cross-sectional echocardiography explores a larger part of the left atrium than the tip of the sampling catheter. Therefore, detection of a few single contrast microbubbles is achieved with a higher level of probability. Unfortunately, there are false negative studies and the method does not allow to assess the size of the shunt.

In patients with a ventricular septal defect, a right to left shunt occurs only in the presence of a right ventricular peak systolic pressure above 45 percent of the left ventricular peak systolic pressure (28). Our findings with echo contrast were similar. There was a right to left passage of contrast in all seven patients where the ratio

of right to left ventricular systolic pressure exceeded 45%. The echo contrast material appears in the right ventricle during the isovolumetric relaxation phase.
It is concluded that diagnostic real time ultrasonic cross-sectional contrast studies using peripheral venous injections of dextrose 5% in water are possible.
Physiologic information is obtained with the correct display of cardiac anatomy in the investigated cross-section. The direction and timing of intracardiac right to left shunts, even when small, are greatly facilitated.
It appears that the sensitivity of echo contrast studies for detecting small right to left shunts might be better than the classic methods.

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CHAPTER 12

ULTRASONIC REAL TIME IMAGING WITH A HAND-HELD-SCANNER

PART II—INITIAL CLINICAL EXPERIENCE

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(*Received in first and final form* 24 *May* 1978)

Abstract—The initial clinical results and potential applications of a miniaturized, battery powered and hand-held ultrasonic imaging device are described. Tests performed in 60 patients on the general cardiology, obstetrics/gynaecology and internal medicine wards demonstrated that good imaging quality and diagnostic information could be obtained on a small display tube.

Key words: Miniaturization, Ultrasonic imaging, Linear array.

INTRODUCTION

This new generation of instrument will make diagnostic ultrasound more readily available where it is so often needed in emergency situations and at the bedside. The device can also be used with great advantage for screening of patients and to optimize more sophisticated examination procedures in the echo laboratory.

Ultrasonic real time imaging is presently accepted as a highly effective and practical diagnostic method and finds increasing application in University and Community Hospitals and even in the physician's offices.

This study reports our initial clinical experience with a miniaturized and battery operated real time ultrasonic imaging device* that allows examination of patients at the bedside. The technical aspects are described in Part I of this paper (Ligtvoet *et al.*, 1978).

CLINICAL RESULTS

For any new and certainly a miniaturized diagnostic imaging instrument, the most important question concerns the image quality. Initial tests were carried out in 60 patients on the cardiology, internal medicine and obstetrical wards. All these patients were also studied in the respective diagnostic ultrasound laboratories. Practical use of the instrument is illustrated in Fig. 1. The quality of the images was comparable to the conventional linear array scanners and similar diagnostic information was obtained. Since no hard copy facility was available, the reported clinical results reflect direct observations based on the investigators' experience. Our clinical results and areas of potential use of the instrument for the three major disciplines can be summarized as follows.

Cardiology

In 19 of the 20 patients, examined at the bedside, it was possible to assess the relative size of both the right and left ventricles and to study the motion pattern of the aortic and mitral valves (Fig. 2). The tricuspid valve was visualized in three patients who had right ventricular enlargement. Moderate pericardial effusion was confirmed in two patients and diagnosed in one patient in whom it was unsuspected. This was subsequently verified in the echo laboratory. Aortic valve vegetations were visualized in a patient right after his hospitalization for suspected infective

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*Minivisor, Organon Teknika, Oss, The Netherlands.

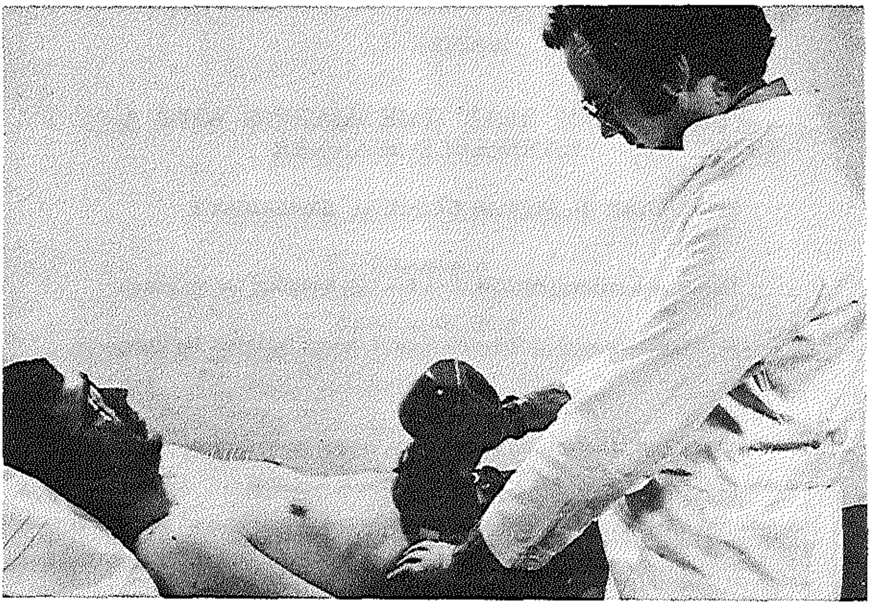

Fig. 1. Examination of the upper abdominal organs with the miniaturized hand-held real time scanner.

endocarditis. We believe that this "ultrasonic stethoscope" is very useful for the differential diagnosis between functional and organic heart murmurs and that a specific diagnosis can often be made. Extrinsic and intrinsic cardiac conditions (e.g. pericardial effusion vs dilated heart, right ventricular vs left ventricular dilation, etc.) are easily distinguished. This is not an uncommon problem in patients seen on the emergency ward and in patients presenting with cardiac failure of unknown etiology at the outpatient department.

Obstetrics and gynaecology

We learned from the patients studied that the placenta, the outline of fetal head (Fig. 3—left image), body and spine as well as fetal body movements and heart activity can be observed as early as 14–15 weeks of gestation. After 22–24 weeks, it becomes possible to visualize the pulsating fetal aorta and the filling and emptying of the fetal urinary bladder.

The clinical use of the instrument has also been evaluated in the antenatal department, the delivery room and the emergency ward. In the antenatal department its great advantage lies in the fact that instant information can be obtained of fetal position, fetal viability and presence of multiple pregnancy. The device also creates the possibility of "on the spot" placenta localization prior to amniocentesis.

In the emergency ward it offers instant information on fetal viability and enables the obstetrician immediately to establish or exclude the presence of placenta praevia in cases of antepartum haemorrhage.

In gynaecology, instant information can be gathered on the presence and position of an intra-uterine device (Fig. 3—right image).

Internal medicine

On the internal medicine ward the prototype demonstrated that ultrasonic exploration of the upper abdominal organs, aorta and retroperitoneal space is easily performed at the bedside. The quality of the images was comparable to that obtained with a conventional, non-focused linear array scanner which is used in our echo laboratory. It allows quick screening of ill patients with doubtful physical symptoms and signs since visualization of intra-abdominal organs or processes is readily available. The instrument can therefore be considered as an "extended

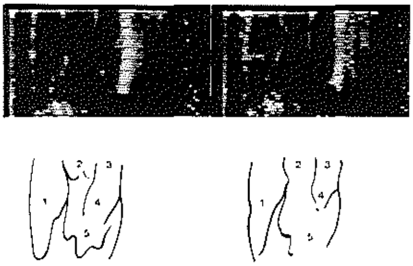

Fig. 2. Long-axis cross-sections of a normal heart. The left frame is obtained in early diastole when the aortic valve is already closed and the mitral valve opens. The right frame is made in mid-diastole with the mitral valve in a central position. The surface area of the left ventricular cavity cross-section is larger on the right frame after ventricular filling. 1. Right ventricular cavity; 2. aortic root; 3. left atrium; 4. mitral valve; 5. left ventricle,

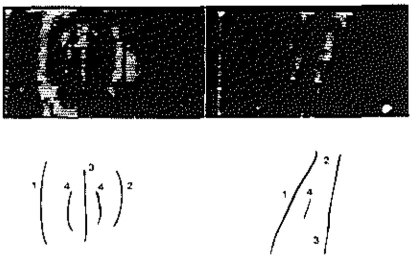

Fig. 3. The left picture shows the fetal head at 32 weeks gestation. 1 and 2. Proximal and distal skull echo; 3. midline; 4. lateral ventricles.

The right picture is a longitudinal section of the uterus with an intra-uterine device in place. 1. Bladder; 2 and 3. uterine cervix and corpus; 4. intra-uterine device.

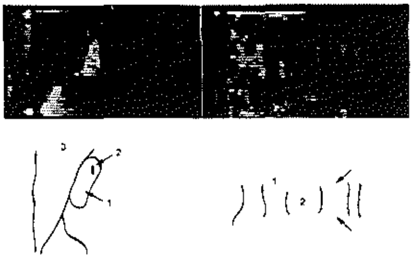

Fig. 4. The left picture shows the longitudinal scan through the liver and gallbladder area. A gallstone is depicted. 1. Gallbladder; 2. gallstone; 3. liver.

The right picture shows a transverse scan through the upper pole of a kidney. A cyst is shown as an echofree area. There is accentuation of sound transmission through the mass with especially strong echoes at the immediate far wall (arrows). 1. Kidney; 2. cyst.

palpation". It was found to be useful in the early differential diagnosis of suspected intra-abdominal abnormalities (e.g. normal vs dilated gall bladder, solid vs cystic space-occupying masses, aortic aneurysms vs peri-aortic lymphadenopathy).

The instrument can be used as a guide to diagnostic and/or therapeutic bedside punctures. It is useful as an aid to tailor more sophisticated B-scanning procedures (defining the proper scanning plane) in order to obtain the maximum amount of information possible or it may even become a substitute for it in emergency situations. Figure 4 shows two examples obtained at the internal medicine ward.

DISCUSSION

Any noninvasive method which images the inside of the body provides major advantages for the analysis of patients.

This possibility is almost unique in diagnostic ultrasound and explains the exploding interest for the method in recent years. The complexity and size of the instrumentation however limits its application at the bedside or in any situation where "urgent decision making" is essential. Immediate and on-the-spot assessment of patients is now possible with this miniaturized, self-contained and battery powered ultrasonic device. Initial results in 60 patients comparing image quality and diagnostic information with that gathered with conventional apparatus in the echo laboratory, showed a good agreement and wide-scale possibilities for its application in cardiology, obstetrics and internal medicine.

It is still too early to evaluate the potential of this new generation imaging device in relation to the more sophisticated ultrasonic examination techniques as performed in ultrasonic laboratories in which the diagnostic value is well established.

We believe that the possibility of bringing the echo laboratory to the patient is a major step forward.

In addition, the device may become very useful when used in association with more elaborate B-scanning procedures or other imaging techniques to define proper scanning planes. Its potential for training ultrasound technologists and bedside teaching is evident.

It is expected that this miniaturized and automated instrument will have an important impact on the diagnostic use of ultrasound and the further development of ultrasonic equipment.

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CHAPTER 13

THE ULTRASONIC CARDIOSCOPE:
A HAND-HELD SCANNER FOR REAL TIME CARDIAC IMAGING

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- Presented at the 51ste Scientific Sessions of the American Heart Association, Dallas, Texas, November 1978.

13.1 SUMMARY

A miniaturized, hand-held ultrasonic scanner which permits portable two-dimensional echocardiography, is described. The device has been routinely used in the casualty department, coronary care unit, ward and outpatient department. The device has advantages in conditions where quick-decision making is madatory in the hands of an expert echocardiographer. It allows an improved analysis of patients with puzzling cardiac conditions at the bedside. An important advance is that the instrument could be used as a substitute for cardiac fluoroscopy in office practice. Tests performed in 100 consecutive patients demonstrated that a reasonable semi-quantitative size estimation of left-sided heart structures is possible. This new generation of instrument can potentially make diagnostic ultrasound more readily available in emergency situations and may have considerable impact on the use of cardiac ultrasound for bedside diagnosis. It will undoubtedly effect further development of automatic, more handy, and special dedicated ultrasonic equipment.

13.2 INTRODUCTION

Improvements in instrumentation (1, 2) and examination techniques (3) have made ultrasonic cross-sectional imaging of the heart into an affective diagnostic tool, which finds increasing use in hospitals and office practices. Most of the efforts to improve the image quality have resulted in the development of more expensive electronic circuitry and in more complex systems. However, the wider application of two-dimensional echocardiography instrumentation may also be determined by such factors as size, portability, ease of use and low cost, all of which would make these studies more readily available provided that the image quality is good.

With these points in mind, we designed and constructed a miniaturized, real time scanner using electronic integration techniques and a small display tube (4).

Battery-powered operation was considered essential for a portable instrument which could be used anywhere.

This study reports our experience with, and the potential clinical use of, this new generation of instrument in clinical cardiology.

13.3 METHODS AND MATERIAL

13.3.1 The ultrasonic cardioscope

The instrument (Minivisor, Organon Teknika) makes use of a linear array of 20 parallel single elements, making up the 10 cm long, 1 cm wide transducer operating at 3.12 MHz frequency. The elements are used in sequence to transmit a single sound beam into the tissues and to receive echoes from the underlying acoustic boundaries. Fast electronic switching across the transducer elements allows the visualization in real time of a display monitor of the cardiac cross-section beneath the linear array (5). The concept and design of this miniaturized battery-operated device was based on several considerations. These include: the integration of all the necessary components in a single shell, low weight, easy operation and control, easy maneuverability with one hand and simultaneous observation of the display screen by the examiner. This resulted in a mushroom-shaped instrument, 25 cm high, weighing about 1.5 kg with its grip area and center of gravity in the middle (Figure 1).

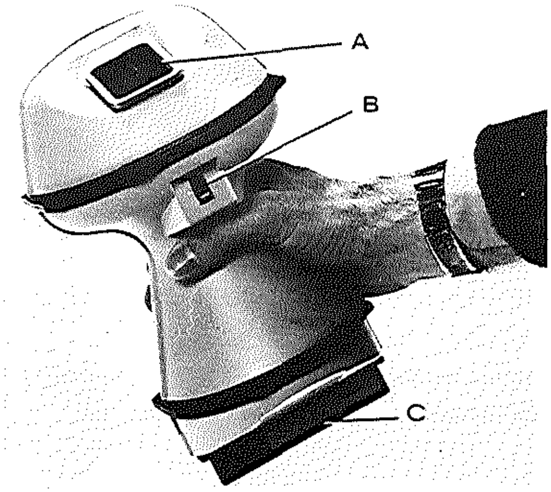

Figure 1.
Photograph of the hand-held ultrasonic scanner showing the small display monitor (A), the switch at thumb level which controls the on/off function and the semi-automatic time-sensitive gain (B) and the linear array transducer (C).

The display monitor has been angled to be easily visible during the examination. The scanned cross-section measures 10 by 20 cm and is represented on the display in a format of two by four cm with a density of 20 lines per cm. Dots enclose the image on the screen and each space between these dots represents 2 cm to assess structure dimensions (Figure 2).

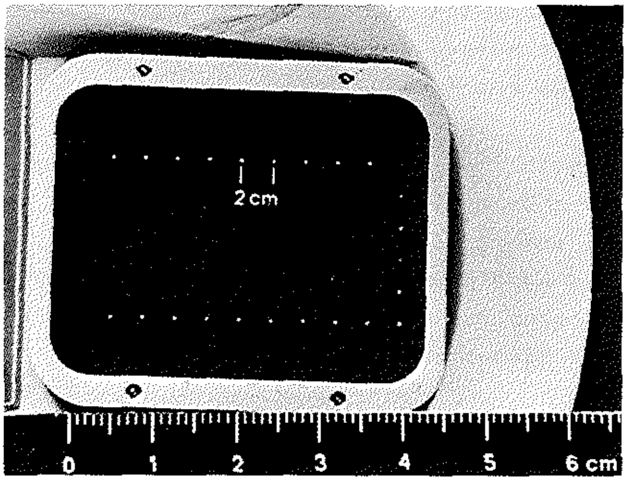

Figure 2.
Detailed photograph of the small monitor screen. The cross-sectional image on the screen is outlined by dots and each space between them represents 2 cm of dimension. They allow for a semi-quantitative estimation of structure size.

Although relatively small, the ratio between the size of the image and its distance to the examiner is similar to that of most conventional two-dimensional systems.
There is only one knob at thumb level which controls the on/off switch and the semi-automatic time-sensitive gain which is based on a feedback principle.
Batteries for pulsing and display are rechargeable NiCd cells and allow continuous operation during 1½ hours. This is adequate for an average day's use. It is also possible to work on main power supply and recharge the batteries simultaneously.

13.3.2 The examination technique

Best position for the examiner is to the left side of the patient who is in a supine or slightly left lateral position. From the left parasternal region, three standard views are routinely studied: 1. the sagittal long axis view from the base of the heart toward the apex of the left ventricle; 2. a short axis view of the left ventricle which is obtained by aiming the interrogating cross-section

perpendicularly to the long axis plane at mitral level and 3. a four chamber view from the midprecordium which is visualized from an intermediate and slightly lower position of the transducer on the chest wall (along the 4th left intercostal space).
The inflow tracts of both the right and left ventricle as well as the atria can thus be visualized. The usefulness and specific clinical information obtained from these cardiac cross-sections have been reported (3, 6, 7).
Other transducer positions are less effectively used since the large aperture transducer requires a rather large ultrasonic window.

13.4 PATIENTS

Initial tests were performed in 50 adult patients (34 males, 16 females; ages ranging from 19 to 63 years) in the outpatient department. It was demonstrated that good imaging quality and diagnostic information could be obtained on the small display monitor (8). To further test whether rational semi-quantitative conclusions about cardiac structural dimensions could be obtained, 100 randomly selected adult patients (61 males, 39 females, ages ranging from 16 to 62 years) were independently studied in the echo laboratory by two investigators. M-mode measurements of different cardiac structures were compared with a semi-quantitative assessment of their sizes from the calibration dots on the small screen.

13.5 RESULTS

Aortic and mitral valve function could be assessed in 83% of all patients (figures 3, 4 and 5).

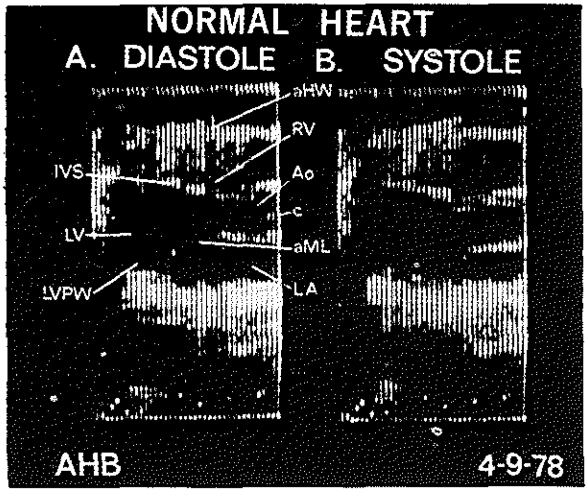

Figure 3.
Cross-sectional images through the long axis of the left ventricle (LV) in diastole (panel A) and systole (panel B) of a normal subject. aHW: anterior heart wall; Ao: aorta; aML: anterior mitral valve leaflet; c: aortic valve cusps in diastole; IVS: interventricular septum; LA: left atrium; LVPW: left ventricular posterior wall; RV: right ventricle.

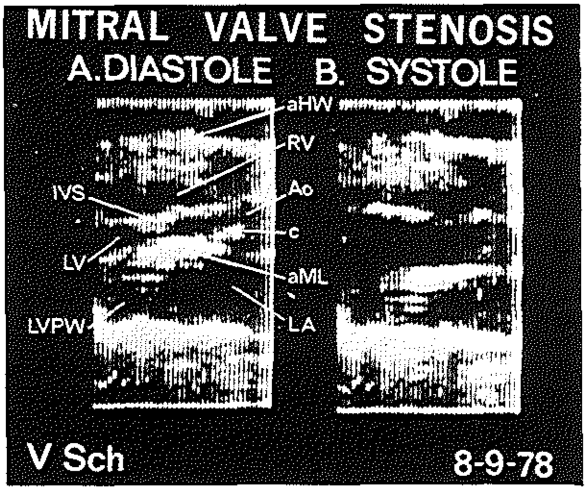

Figure 4.
Paired diastolic (panel A) and systolic (panel B) left ventricular long axis views of a patient with severe calcific mitral valve stenosis. Note the calcific thickened anterior mitral valve leaflet (aML) and fused chordae. aHW: anterior heart wall; Ao: aorta; c: aortic valve cusps in diastole; IVS: interventricular septum; LA: left atrium; LV: left ventricle; LVPW: left ventricular posterior wall; RV: right ventricle.

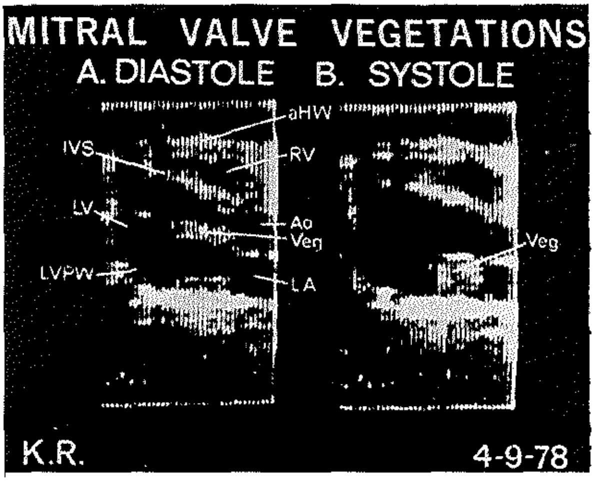

Figure 5.
Diastolic (panel A) and systolic (panel B) frames obtained from a patient with bacterial endocarditis and vegetations (Veg) on the anterior mitral valve leaflet. Note the thickening of the leaflet which demonstrates good mobility. aHW: anterior heart wall; Ao: aorta; IVS: interventricular septum; LA: left atrium; LV: left ventricle; LVPW: left ventricular posterior wall; RV: right ventricle.

The right ventricle was difficult to analyse unless it was dilated, mainly because of poor definition of the anterior cardiac wall and the presence of non-structural echoes in the cavity. The interventricular septum was well delineated in most patients and left ventricular shape and wall dynamics could be appreciated in 89% (Figure 6).

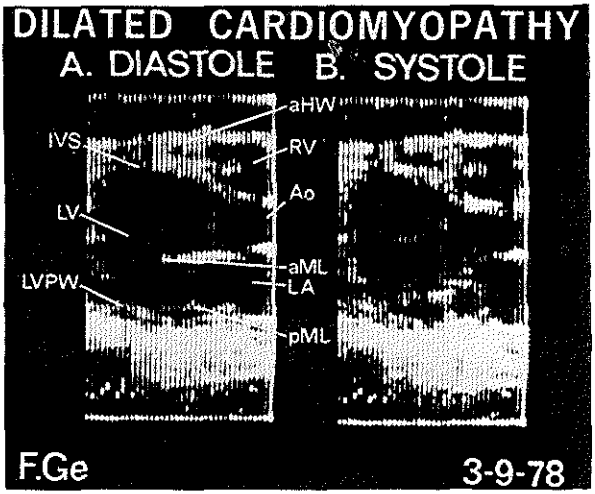

Figure 6.
Diastolic (panel A) and systolic (panel B) frames obtained through the long axis of the left ventricle from a patient with dilated cardiomyopathy. Note the globular shape of the left ventricle (LV). aHW: anterior heart wall; Ao: aorta; aML and pML: anterior and posterior leaflets of the mitral valve; IVS: interventricular septum; LA: left atrium; LVPW: left ventricular posterior wall.

Aortic root dimension was classified either on an ordinal scale as normal (when $\leq$ 4 cm), abnormal (when exceeding 4 cm) or was unmeasurable. These assessments were compared with a classification from the M-mode measurements with the same cut-off points. In six patients it was impossible to assess the aorta with the ultrasonic cardioscope. In one of them this was also impossible for the M-mode. There was agreement between the two methods in 92 of the remaining 94 patients. In the other two cases, the investigator using the ultrasonic cardioscope overestimated the aortic size. Left atrial size (the dimension between the posterior aortic and left atrial walls at aortic valve cusp level) was classified either as normal when $\leq$ 4 cm, enlarged if more than 4 cm or severely enlarged if greater than 6 cm.

It was unmeasurable in five patients because of poor definition of the left atrial posterior wall. In two of these this was also impossible from the M-mode. In the remaining 95 patients, there was agreement in 78 and no agreement in 17 patients. The examiner with the ultrasonic cardioscope tended to overestimate the left atrial size and this tendency was statistically significant at the 5% level in a two-sided test (McNemar test) (9) (Table I).

MINIVISOR

M-MODE	NL	>	>>	U	
< 4 cm	56	8★	1	2	
4-6 cm	1★	20	7	1	
> 6 cm	-	-	2	-	
U	-	-	-	2	2
				5	

★ $p < 0.05$ (McNemar test)

Table I: accuracy of left atrial size assessment with the ultrasonic cardioscope (100 consecutive patients)

NL = normal; > = enlarged; >> = severely enlarged;
U = unmeasurable

Left ventricular size was estimated from its semi-minor axis dimension and classified either as normal, enlarged if more than 5,5 cm or severely enlarged if greater than 7 cm. It was unmeasurable in 11 patients. It was identical to the M-mode classification in 66 patients. In the remaining 23 patients, the investigator with the ultrasonic cardioscope overestimated the ventricular size in 18 patients. This is also statistically significant at the 5% level in a two-sided test (Table II).

MINIVISOR

		NL	>	≫	U	
M-MODE	< 5.5 cm	43	16★	–	8	
	5.5 - 7.0 cm	5★	17	2	3	
	> 7.0 cm	–	–	6	–	
	U	–	–	–	–	0
					11	

★p < 0.05 (McNemar test)

Table II: Accuracy of left ventricular size assessment with the ultrasonic cardioscope (100 consecutive patients).

NL = normal; > = enlarged; > > = severely enlarged;
U = unmeasurable

13.6 DISCUSSION

Ultrasonic imaging of the heart has been one of the most rapidly developing diagnostic techniques in use today. The first clinical results which stimulated considerable interest in the method were obtained with a real time linear array scanner and were reported in 1973 (10). This rapid acceptance is explained by the unique potential for gaining significant information about cardiac anatomy and function without known risk to the patient. The complexity and size of the instrumentation however, has limited its application at the bedside or in any situation where "quick-decision making" is essential. In fact, most equipment is currently used in a laboratory or examining room to which the patient must be transported. Bedside examination can be facilitated since this miniaturized and battery-powered device can be used in a manner analogous to a conventional stethoscope. In this way, it extends the perception of clinical examination since physical findings such as sounds or movements can be immediately related to anatomic abnormalities in most of the patients studied.
It therefore promises improved analysis of patients with puzzling cardiac murmurs or those with cardiomegaly, some of the most common dilemmas in bedside examination, since it provides information beyond that which the physical examination can obtain.
Our study demonstrated that, although the instrument cannot be used for quantitative measurement of cardiac structure dimension, it may provide a semi-quantitative estimation of the size of cardiac structures at least in those patients in whom good image quality is obtained. It should be realized, however, that this is a first generation instrument·an that improvements will provide better resolution and therefore more accurate measurements. The instrument has now been routinely used over a period of six months in the emergency department, coronary care unit, wards and outpatient department (Table III).

Table III

USEFULNESS OF ULTRASONIC CARDIOSCOPE

EMERGENCY DEPARTMENT, CCU

- Quick-decision making
  (to differentiate between tamponade, enlarged heart or cardiomyopathy)

- Gauge effects of interventions
  (pericardiocentesis, proper insertion of balloon-tipped catheters, etc)

HOSPITAL WARDS

- Immediate answer to clinical problems
  (cardiomegaly, murmurs, silent valvular heart disease, etc)

OUTPATIENT DEPARTMENT, OFFICE PRACTICE

- Substitute for cardiac fluoroscopy

It has been useful for the differential diagnosis between some functional and organic murmurs (e.g. mitral valve stenosis vs Austin-Flint murmur) and for the immediate distinction between extrinsic (pericardial effusion) and intrinsic causes of cardiac dilatation (right ventricular vs left ventricular dilatation). In addition, a variety of specific clinical diagnosis were made. In the emergency department and coronary care unit where the use of a conventional apparatus is cumbersome, it is now routinely employed to differentiate between tamponade and a dilated heart. This constitutes the most important clinical application. Over a period of one year there were seven recorded instances in which this differential diagnosis was made by the consulting cardiologist in critically ill patients in city hospitals of Rotterdam, where no other echo facilities were available. The differential diagnosis between tamponade and right ventricular infarction has been made in patients with acute myocardial infarction. The study of the distribution pattern of pericardial effusions has been extremely helpful for performing and monitoring a pericardiocentesis. In the hospital ward and outpatient department it may give immediate answers to some diagnostic dilemmas and thus has advantages in teaching students. In office practice, it can be used as a substitute for cardiac fluoroscopy allowing the estimation of the relative size of cardiac cavities with assessment of wall and valvular dynamics.

The device has been tested before hard copy facilities were available. In fact, the illustrations shown in this paper were obtained by direct photography of the monitor oscilloscope. It is obvious that images from the small screen are difficult to record and that the photographic process degrades the image quality which at present is already marginal during real time examination. In addition, it must be realized that the visual integration of structure motion provided by real time scanning cannot be experienced from stop-frame images as presented in this paper. At present, images can be recorded on video tape via a scan-converter, but this requires the use of expensive additional equipment and detracts from the major advantage: its portability. The capabilities of the instrument are indeed greatest when it is used for immediate diagnosis in a way similar to that of a conventional stethoscope.

Needless to say that for the present, the application of the instrument is limited and its proper use requires extensive clinical experience with standard cross-sectional imaging devices. It therefore should not be recommended as a substitute for conventional systems but rather as a readily usable stand-by in experienced laboratories for the applications discussed.

We feel that this new generation of instrument will have an important impact and will lead to widespread use of diagnostic ultrasound in clinical practice. It may further stimulate the development of automatic miniaturized and cheaper equipment.

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CHAPTER 14

PRESENT STATUS OF ULTRASONIC TWO-DIMENSIONAL CARDIAC IMAGING AND A PERSPECTIVE INTO THE FUTURE

The ideal diagnostic imaging system should yield definitive data concerning the cardiac condition of a patient with a maximal success rate. It should cause no harm or discomfort and should be convenient, reliable, and economical. Cardiac ultrasound meets most of these specifications. The procedure is noninvasive and no harmful effects have been reported. The method can be applied rapidly, repeatedly and yields quick results. Most criteria tested in M-mode echocardiography are well validated and the description of common cardiac disorders seem to be adequate for two-dimensional echocardiography.
These factors explain the continued high interest in the method and the distinctive role it plays alongside other diagnostic imaging methods today. At the Thoraxcenter, the number of requests for echocardiographic examination has increased from 65 per month in 1973 to 280 per month in 1978. However there are some inherent limitations related to both the method and the kind of patient that can be studied with success. In addition a great deal of experience is needed for obtaining and interpreting the data. It is the purpose of this chapter to discuss some of these aspects and some specific problems related to the multiscan approach.

14.1 COMPARISON OF ULTRASOUND, X-RAY AND NUCLEAR IMAGING

To a great extent, the form of energy chosen delineates the specific indications, advantages and disadvantages for each of these commonly employed clinical imaging techniques. Diagnostic ultrasound utilizes sound radiation which is harmless at the levels used. Most other imaging techniques employ ionizing energy. This is an important advantage to consider as both examiners and patients become more and more conscious of the longterm effects of repetitive exposure to even small amounts of ionizing radiation(X-rays, radionuclides). It is now established that ultrasound examinations can be easily and often repeated without untoward effects and it may therefore become the principal method for the serial analysis and follow-up of cardiac patients to name but one category. With ultrasound, local changes in acoustic impedance along the beam pathway are registered. X-ray techniques register cumulated attenuation of energy along the pathway so that cardiac structures are superimposed in depth and are seen as shadows. In other words, X-ray measurements do not provide "information" at each point in depth whereas ultrasound does. This allows the detection of internal cardiac structures as well as their motion and dimension. As a result, the specific details of intracardiac anatomy and pathology, such as the attachment and morphology of atrioventricular valves, the interventricular septum etc, are much easier and better documented with ultrasonic two-dimensional imaging than by X-ray techniques. This advantage together with the possibility of rapid sampling and the lack of irreversible effects of ionizing radiation makes ultrasound techniques the preferred approach to dynamic two- and three-dimensional analysis of the heart. The unique potential of visualizing intracardiac anatomy must be directed toward evaluating new parameters of cardiac function rather than of those which at present are largely derived from angiocardiography. Also ultrasonic examination should be increased in order to reduce the number of potentially hazardous angiocardiograms and eliminate these invasive studies entirely in specific groups of patients where careful testing of its diagnostic accuracy has established its supremacy. X-ray techniques with contrast enhancement have the advantage of high definition, e.g. for visualization of the anatomy of the coronary arteries. Here, they will undoubtedly remain the principal and definitive diagnostic method. Ideally therefore two-dimensional echocardiography should be integrated into the routine catheterization procedure since it makes spatial morphology of cardiac structures available. This allows direct visualization of ruptured and thickened parts of the valves, their orifice areas and small masses such as tumors and infective vegetations. As this information is not available from X-ray studies, the combination of both approaches while the patient is on the cardiac catheterization table, appear a highly useful concept. As stated, because of the radiation exposure and potential morbidity, X-ray imaging cannot readily be repeated and must be considered as a "single-shot procedure", which requires a deliberate and meticulous indication. Instead of viewing ultrasonic imaging as competitive, it should be considered as a most useful complementary method in planning the definitive diagnostic procedure.

Portable cross-sectional echocardiography is now possible with a miniaturized hand-held scanner and makes the imaging method readily available at the bedside and more importantly in office practice. With the improvement of image quality in the near future, this method will replace many cardiac fluoroscopic examinations.

Nuclear imaging techniques are able to provide information which is not available by X-ray and ultrasound methods. In addition to information on myocardial perfusion and its viability, nuclear imaging is able to provide quantitative information on cardiac performance and regional wall motion during excercice in patients with coronary artery disease. Excercise ultrasonic imaging is extremely difficult to perform and the success rate in obtaining interpretable ultrasonic data in the large group of patients with coronary artery disease is decreased to 70%. Therefore, nuclear imaging will probably become the principal method for testing patients with coronary artery disease. However, it may well be that this will be the category of patients to profit from the newer applications of ultrasound. These will give insight into the status of the myocardium by the analysis of ultrasound parameters such as velocity, absorption and scattering.

14.2 M-MODE VERSUS TWO-DIMENSIONAL ECHOCARDIOGRAPHY

The basic difference between M-mode and two-dimensional echocardiography was extensively discussed in chapter 2. The final clinical capabilities of two-dimensional ultrasonic imaging of the heart are still unsettled and its relative advantage over M-mode echocardiography is still controversial. Basically both methods differ in the display of the ultrasonic information.

The M-mode examination procedure is mainly confined to the parasternal "ultrasonic window" since the information obtained via other "windows" is limited by the lack of a spatial reference. As a result, the M-mode examination technique is restricted to M-mode scanning of the left ventricle and recording the tricuspid and pulmonary valves. This means that routine M-mode echocardiography is readily standardized so that it can be performed by a well trained technician. Another advantage of M-mode echocardiography is that the familiar stripchart record is obtained. This can be rapidly analyzed and allows simple but diagnostically important measurements. This analysis can be done off-line in ideal circumstances. The data are easily stored and retrieved.

Two-dimensional studies of the heart are much more demanding than M-mode despite the more familiar looking display which anatomically resembles the heart. Four "ultrasonic windows" instead of one, are now routinely used and the number of cross-sections which can be studied, is in principle, unlimited (1, 2). Some cardiac structures such as the interatrial septum, right atrium and right ventricle, are imaged to much greater advantage by cross-sectional than M-mode techniques. Thus, the diagnostic yield of two-dimensional echocardiography is potentially much higher. However, the complexity of the examination during which the patient's history and other clinical findings should be taken into account would require the interaction of a trained cardiologist. Only he can assess the clinical problem and redirect the examination in order to solve the clinical question. This situation is similar to that in the catheterization laboratory. The examination when done by a technician takes a longer time since many unnecessary views are recorded in order not to miss potentially relevant information. Furthermore, off-line analysis of two-dimensional images is not very practical. Retrieving the data from video recordings is cumbersome and the analysis is almost as time consuming as the real study itself. It therefore appears that the multitude of imaging possibilities requires an integrated approach to effectivily solve a patient's clinical problem in a short period of time. Thus, ideally a cardiologist would perform the two-dimensional examination. This will be hard to realize in practice. Indeed, it does mean that a full-time cardiologist would be available in laboratories with a high patient load. The problem can probably be solved in the future with portable devices which make the two-dimensional image available to the cardiologist anywhere it is needed, provided of course that the image quality is as good as that of presently available laboratory instrumentation.

14.3 PATIENT AND CARDIAC ANATOMY RELATED PROBLEMS OF TWO-DIMENSIONAL ECHOCARDIOGRAPHY WITH MULTISCAN

Ultrasound is highly attenuated in air which makes lung tissue virtually impenetrable. As a result, the "ultrasonic windows" on the chest wall from which ultrasound beams can be directed into cardiac structures are limited and small. The acoustic mismatch between bone and soft tissue is also great. If one tries to direct a sound beam through bone, almost all of the ultrasound energy is reflected or absorbed. Thus, an ultrasonic examination is impractical or impossible when the transducer is placed over the sternum or a rib. The problem is not as great in infants and young children since these structures usually are not calcified. However, in adults the sternum and ribs restrict the effective area of the "ultrasonic windows". In practice, four transducer positions on the chest wall can be utilized: the parasternal area, the apical area, the subxiphoidal or subcostal area and the suprasternal notch (1, 2). Cross-sectional views of the heart relative to its long and short axes can be obtained from each of the first three transducer positions and those of the great vessels from the suprasternal notch position. The latter position is extremely important for the analysis of complex congenital malformations. The major limitation of the linear array transducer is its large size. This limits the examination of the heart mainly the parasternal position. Many views can thus not be visualized. The apical transducer position is of particular clinical importance and is now becoming the standard position for the study of the apical segment and quantitative analysis of the left ventricle. Unfortunately, it is rare to obtain good quality images from the apical position with the linear array transducer. Most cardiac structures are readily visualized with a high success rate from this position by sector scanner devices employing a smaller transducer head.

The ability to manipulate a linear array transducer within the confines of the parasternal ultrasonic windows is further limited by its size. As a result, proper angulation to visualize cardiac areas which are eccentrically located in relation to this ultrasonic window, such as the apex of the left ventricle, remains a problem. Also the lateral parts of the transducer loose acoustic contact with the patient's chest and cause a loss of image.

A small parasternal ultrasonic window as a result of obstructive airway disease is the most common cause of failure to obtain adequate two-dimensional images in patients with coronary artery disease. This further limits the capability of the techniques to study the left ventricle in older and coronary patients, who represent the largest group of patients seen by the adult cardiologist. The success rate in visualizing the apex using a linear array transducer was found to be 7% in our laboratory in a study performed by Dr. R. Meltzer. In the literature success rate between 70 and 90% have been reported with sector scanners. Thus, patient suitability may represent a major limitation to the ultrasound method and will definitely indicate the type of instrumentation to be used.

The small diameter of the sector scanner transducer allows its placement between ribs and maintenance of contact with the skin during transducer angulation. This constitutes the major advantage of these systems and accounts entirely for the high success rate in obtaining adequate images of the entire left ventricle.

In our clinical experience, target "drop-out" is more frequently observed with a linear array transducer than with a sector scanner. Specifically, parts of the interventricular septum are not visualized in most of the patients studied. It is also uncommon to obtain a good image of the interatrial septum. The sloping posterior wall of the left ventricle in the area of the postero-medial papillary muscle, as it inclines towards the apex is frequently not recorded. Good images of these structures are usually well obtained with a sector scanner. Only part of this observation is explained by the intervening rib structures and the limited aiming capabilities from the parasternal position with a large and rigid linear array transducer.

Theoretically, target "drop-out" can also result when the sound beam to target relationship is not maintained in a perpendicular direction. Thus, the complex geometry of the heart would make target "drop-out" to be common on cross-sectional images. However, cardiac structures are sound scatterers rather than specular reflectors. In addition, the sound beams are integrating information from a rather large irregular surface area. Thus, the observed differences in occurence of target "drop-out" with these two different

imaging systems cannot be explained on the basis of reflection characteristics alone of these targets.
It appears that the explanation of target "drop-out" is complex.
It is the author's opinion that the small ultrasonic windows to the heart dictate a small size for a transducer. Also, the shape of the heart may make sector scanning more effective than linear array instruments. In this way, a large field of view without shadows of blind spots can be achieved through the limited acoustic window with better aiming capabilities. The instrument of choice will be an electronic rather than a mechanical sector scanner because of the higher frame rate, reliability, and more compact form of its probe.

14.4 INSTRUMENT RELATED PROBLEMS IN TWO-DIMENSIONAL IMAGING

Several physical factors limit the diagnostic capabilities of presently available two-dimensional imaging systems. Their small dynamic range is unable to display all the available echo information and as a result, many weak reflectors within the heart are not seen. Newer instruments will undoubtedly have a wider dynamic range than the present instruments through the use of custom integrated circuit electronics which are being developed for medical ultrasound applications. Since the majority of the electronic components in present ultrasound systems were designed for other applications rather than ultrasonic imaging, considerable improvement may be expected from customized ultrasonic integrated circuit design. As was extensively discussed in chapter 10, the finite sound beam width limits the resolving power and causes spurious echoes on the display. This may lead to interpretation errors. The transducer is responsible for most of the resolution limits of an imaging system. Much research presently being done is aimed at improving the lateral resolution and transducer performance and will undoubtedly yield a much better image quality during the next few years. From the clinician's point of view, the ultrasonic instrumentation should also be simple to use, portable (see under 14.2), and the transducer must be small (see under 14.3).

14.5 ECHOCARDIOGRAPHER RELATED PROBLEMS IN TWO-DIMENSIONAL IMAGING

Two-dimensional echocardiography has been developed after the generation of cardiologists now in practice had completed their formal training. Its rapid development and implementation as a diagnostic method has profoundly altered the practice of cardiology. Not much time, however, has been left to develop a full understanding of both its advantages and limitations. The method is highly demanding. It requires an integrated comprehension of cardiac anatomy, pathology and physiology. The interactive examination technique requires knowledge of the physical aspects of ultrasound imaging and of the specific characteristics of the particular ultrasound apparatus being used.

Some of the instrument functions will become automated with the more sophisticated integrated electronic technology. In addition, these will also allow advanced and rapid quantitative data analysis.

Diagnostic functions will be incorporated into imaging systems to assist in performing measurements. Nevertheless, choosing the correct clinical application, deciding what the method can or cannot do and interpreting the results will be left to the echocardiographer. This poses serious problems for the training of both clinicians and technicians. Most practicing echocardiographers learned the technique through self-study and on the job training. No assessment has been made as to whether this is an effective way of learning. Short introductory courses for both clinicians and technicians are now regularly organized at many centers in the USA. In Europe, such programs are only offered in a few countries.

Since 1975, we have organized six 4-day courses per year limited to 15 participants only at the Thoraxcenter. The Interuniversity Institute of Cardiology sponsors six evenings per year which are attended by many echocardiographers. Again, the effect of these activities on the quality of clinical echocardiography is not known, but it can be expected to expand the utilization of these techniques. For continued education, short courses are undoubtedly very helpful.

There is certainly a large need for further educational programs. The author believes that such programs should be sponsored and organized by the Dutch Heart Foundation.

14.6 NEW DEVELOPMENTS

Presently, the diagnostic information in two-dimensional images is obtained from the display of ultrasound reflective boundaries. Fortunately many studies are now underway to acquire "tissue-signature" information, that is, information about tissue pathology from a quantitative analysis of the reflected ultrasound signal. The results of in vitro analysis of amplitude histograms from normal and infarcted myocardium are encouraging and the method is presently being tested to map early infarcts in man (3). The integration of blood flow data would further complement two-dimensional ultrasonic information. The possibility of visualization and measurement of blood flow simultaneously with two-dimensional images has already been implemented in a peripheral vascular prototype instrument (4).

Such devices when made suitable for cardiac examination will allow detection of lesions manifested by blood flow abnormalities rather than only by anatomic abnormalities. This will improve echocardiographic diagnosis of small degree of mitral insufficiency and small ventricular or atrial septal defects.

Cardiac output measurement may become possible in the near future by combining the information from the cross-sectional area of a great vessel and angular incidence of the interrogating Doppler beam providing the flow velocity data.

Another approach toward measurement of volume dependent indices of cardiac function is offered by quantitative contrast echocardiography using the indicator dilution principle. A far fetched goal is the noninvasive pressure measurement using precision microbubbles. Resonant frequency of these microbubbles changes with ambiant pressure and can be detected with an ultrasonic transducer (5).

14.7 ECONOMIC ASPECTS

When compared to other imaging methods, cardiac ultrasound is not an expensive diagnostic method. Newer instrumentation will probably become cheaper despite greater performance and increasing electronic complexity. This trend has already started and follows the one observed in the semiconductor industry (6). Special dedicated portable devices with a high diagnostic yield will become available in near future.

Their widespread use will further reduce the costs of medical diagnosis since many expensive and invasive procedures will be replaced. Full realization of these potential benefits might take one generation of cardiologists however, since physicians tend to continue clinical patterns acquired during their specialty training, a sad reflection upon the (in)flexibility of man.

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HOOFDSTUK 15

SAMENVATTING

In deze studie wordt de klinische evaluatie beschreven van een twee-dimensionaal echocardiografisch systeem (multiscan), dat werd ontwikkeld op het Thoraxcentrum van het Academisch Ziekenhuis Dijkzigt te Rotterdam.
Met dit systeem kunnen doorsneden van het bewegend hart zichtbaar worden gemaakt. Een voordeel is dat deze onderzoekmethode niet schadelijk is voor patient en onderzoeker.
De algemene principes van de ultrageluidsdiagnostiek zoals toegepast in de cardiologie worden beschreven in hoofdstuk 2.
De ontwikkeling van de twee-dimensionale echo systemen wordt kort besproken in hoofdstuk 3 en de verschillende aspecten van het multiscan systeem, onderwerp van dit proefschrift, worden behandeld in hoofdstuk 4.
Toen we in 1973 het eerste apparaat ter beschikking kregen in de cardiologische kliniek, bestond er geen goede beschrijving van de anatomie van het hart zoals deze met de nieuwe techniek zichtbaar wordt gemaakt. Onze eerste studies waren dan ook gewijd aan structuur identificatie en het uitwerken van een gestandaardiseerde onderzoekmethode. De resultaten hiervan zijn weergegeven in de hoofdstukken 5-7.

Omdat de omtrek van de linker hartkamer verkregen in de sagittale lange as doorsnede lijkt op een angiocardiogram, werd er logischerwijze geprobeerd om in analogie met deze methode de ultrasonore doorsneden kwantitatief te analyseren.

Na bemoedigende resultaten bij een eerste groep patienten (hoofdstuk 8), bleek nadien dat er toch geen goede relatie bestond tussen de linker kamer volumina gemeten door middel van angiocardiografische en echocardiografische methoden (hoofdstuk 9). De redenen hiervoor worden besproken in hoofdstuk 10. Deze gegevens vormden de basis voor het ontwikkelen van een systeem met een beter oplossend vermogen en definitie van de hartstructuren.

Van verschillende kwalitatieve studies die we hebben ondernomen, is de twee-dimensionale kontrast echocardiografie verreweg de belangrijkste. Door het inspuiten van enkele cc's dextrose 5% in water is het mogelijk om naast de hartstructuren ook het bloed in de rechter harthelft zichtbaar te maken. Het effect verdwijnt in het longvaatbed en er komt nooit echokontrast in de linker harthelft. Gebeurt dit toch,dan is een rechts-links shunt bewezen. Uit ons onderzoek is gebleken,dat deze methode gevoeliger is dan zuurstof saturatie metingen (hoofdstuk 11).

Met de opkomst van de micro-electronica lag het voor de hand aan miniaturisatie te denken en een draagbaar tweedimensionaal echo systeem te ontwikkelen. Dit werd verwezenlijkt met de ultrasonore cardioscoop (hoofdstuk 12). Mogelijke toepassingen van dit apparaat in de cardiologie worden besproken in hoofdstuk 13. Het is duidelijk dat een dergelijk systeem een grote invloed zal hebben op de verdere ontwikkeling van kleinere diagnostische systemen die aan het ziekbed kunnen worden toegepast.

In hoofdstuk 14 worden de mogelijkheden en ook de beperkingen van de twee-dimensionale echocardiografische diagnostiek besproken en vergeleken met andere beeldtechnieken. De beperkingen van de techniek liggen hoofd-

zakelijk bij de patient. Het hart is immers omgeven door lucht, die geen ultrageluid doorlaat, en door benige ribstructuren. De ingangen voor de onderzoekende ultrageluidsbundels zijn dus beperkt en klein. Een kleine wendbare transducer is derhalve wenselijk.
Twee-dimensionale echocardiografie moet ongetwijfeld als één van de belangrijkste aanwinsten worden beschouwd in de cardiologie sinds het invoeren van de stethoscoop door Laennec.

CURRICULUM VITAE

José Rufin Theo Clement Roelandt werd geboren op 12 november 1938 te Erembodegem (België). In 1957 verkreeg hij zijn diploma Grieks-Latijnse Humaniora aan het Sint-Jozefscollege te Aalst. In dat jaar begon hij met de medische studie aan de Katholieke Universiteit te Leuven. In 1960 werd het kandidaatsexamen en in 1964 het diploma doctor in de genees-heel- en verloskunde behaald. Aan dezelfde universiteit begon hij direct hierna zijn specialisatie in de Interne Ziekten onder leiding van Prof. Dr. J. Vandenbroucke, welke in 1967 werd vervolgd in de Cardiologie bij Prof. Dr. J.V. Joossens. In 1968-1969 werd deze opleiding voltooid op de afdeling Cardiologie van het Academisch Ziekenhuis te Leiden onder leiding van Prof. Dr. H.A. Snellen.
Eind 1969 werd hij benoemd als wetenschappelijk medewerker aan het Thoraxcentrum van het Academisch Ziekenhuis Dijkzigt van de Erasmus Universiteit te Rotterdam.
In 1976-1977 was hij als gasthoogleraar verbonden aan de afdeling Cardiologie aan het University of Oregon Health Sciences Center (USA).
Hij is Fellow van de American College of Cardiology, voorzitter van de werkgroep Echocardiografie van de European Society of Cardiology en de eerste niet-Amerikaan die werd verkozen tot lid van de Board of Directors van de American Society of Echocardiography.

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