

~~ASPECTS OF~~ TWO - DIMENSIONAL ECHOCARDIOGRAPHY
IN CLINICAL CARDIOLOGY

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III

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INTRODUCTION AND SUMMARY

Pioneering two-dimensional echocardiography with triggered B-scanning in Great Britain made it necessary to develop a scanning technique and an anatomical orientation with this method which would fit into the prevailing understanding of cardiac anatomy as obtained from anatomy, pathology, angiocardiology, and one-dimensional or M-scan echocardiography.

The subsequent experience with all other possible echographic methods discussed in this thesis, such as multi-element systems in the form of mechanical or electronical real-time B-scanners, proved this technique to fulfil all the requirements necessary for any echographic investigation of the heart.

The equipment, scanning techniques and diagnostic potential of the Continuous Sweep Technique, triggered and real-time B-scanning are discussed and correlated with the results of M-scan echocardiography in particular diseases.

Emphasis has been placed on the understanding of those physical phenomena often used in echocardiography or which are related to a different understanding of some echographic presentations, and consequently on the limitations of the various techniques. In the example of septal motion in hypertrophic cardiomyopathy real-time B-scanning has thus aided in explaining the role of the septum in the haemodynamics of this disease.

The comparison of all B-scan results with those from M-scanning led to a re-evaluation of the latter technique, and in the case of hypertrophic cardiomyopathy to a change of diagnostic criteria and a new insight into the pathophysiology of this disease.

The comparison of functional data obtained from angiocardiology and two-dimensional echocardiography shows that

the two-dimensional evaluation not only of cardiac anatomy but also of cardiac function may, in suitable patients, be the diagnostic procedure of choice, since it is non-invasive and therefore unlimitedly repeatable.

This may be true particularly in those patients where intracavity pressures are not the most important data for assessing the appropriate means of medical or surgical therapy.

HISTORICAL REVIEW

Reflected ultrasound, as initially used in industrial non-destructive testing of materials for the presence of flaws, was first utilised to examine the human heart by Edler and Hertz in 1953¹. They called this investigation "Ultrasoundcardiography". With the initial echograph, an industrial machine from Siemens, Germany, only the posterior wall of the heart was visualised. With modifications it became possible to scan the anterior leaflet of the mitral valve, which, however, was initially believed to represent the left atrial posterior wall¹⁻³. Only when these structures were investigated by using needles in postmortem hearts, was the origin of the anterior mitral valve leaflet recognised⁴. Thus, it was soon possible to detect mitral stenosis as the first pathological situation to be diagnosed by ultrasoundcardiography. In Germany a group around Effert started with ultrasound investigations of the heart in 1956 and confirmed the work of Edler and Hertz⁵. Their work also led to the valuable distinction between mitral stenosis and left atrial tumours in 1959⁶. Another group in Germany, Schmitt and Braun from Würzburg, took up ultrasound cardiology and again confirmed the work on mitral stenosis previously done⁷. They also evaluated ultrasound in the diagnosis of congenital heart disease⁸. In 1961 Edler and Hertz published a comprehensive review of ultrasoundcardiography in the diagnosis of mitral stenosis, mixed mitral valve disease, left atrial myxoma, and pericardial effusion⁴, and most of their criteria are still valid today.

The first attempt in America to use diagnostic ultrasound in cardiology was undertaken by Joyner and Reid in 1963⁹. In 1965 a group around Feigenbaum published their work on pericardial effusion, confirming and enlarging on the work of Edler and Hertz¹⁰. From that time on a great deal of work was done in the United States, confirming previous work done in Europe and finding new applications in diagnostic ultrasound.

Another stimulus for diagnostic ultrasound was given in 1969 with the possibility of confirming current echographic techniques by injection of indocyanine green dye and saline, which outlined the different heart chambers and thus determined their borders¹¹.

The term 'echocardiography' was formulated by the American Institute of Ultrasound in Medicine and widely accepted, although what they were referring to was the one-dimensional technique, for which we prefer the term 'M-scan echocardiography' in order to differentiate from Doppler echocardiography and the two-dimensional imaging techniques, such as triggered and real-time B-scan echocardiography.

A major landmark in echocardiography was the introduction of two-dimensional imaging of the heart. The Japanese were most active in researching stop action and real-time B-scan cross-sectional cardiology^{12,13,14}. The main credit, however, for stimulating world-wide interest in the use of real-time B-scan echocardiography came from Europe and must be given to the Dutch Engineer N. Bom, who developed a multi-element system in 1971 and published the technical descriptions of his machine and the first clinical applications in 1973¹⁵.

I became interested in echocardiography in early 1973 when I started with M-scan and triggered B-scan echocardiography simultaneously. The triggered B-scanner, the Echo View IV Laminograph from Picker Company was given to us for clinical evaluation by courtesy of General Electric Corporation Ltd., London. At the time very little information was available about this scanning technique, so that we had to develop our own techniques.

Later in 1973 I had the opportunity¹⁶ to judge the prototype of the Dutch multi-element system, which was to be evaluated by Dr. Pridie¹⁷, Consultant Radiologist at Harefield Hospital, Middlesex, and also at Hammersmith Hospital at

the time. He must be credited for introducing echocardiography in this Hopital. The first results from the multi-element system¹⁷ convinced us that the possibilities offered by real-time would be most important if the lateral resolution (see p.17) reached the quality of that in triggered B-scanning. However, seeing improving results from the multi-element system of N. Bom and also seeing the potential of an old demonstration model of a mechanical real-time B-scanner, the 'Vidoson 635', I decided to start with real-time and we arranged for a newer model, the 'Vidoson 635S', to be sent over from Germany by courtesy of Siemens in Erlangen. We regarded it a challenge to pioneer this equipment for routine use in cardiology, since this machine had been commercially available since 1967¹⁸ and originally designed for heart investigation. Its value was not appreciated by cardiologists then, so that the equipment had been re-designed for work in obstetrics. I started work in mechanical real-time echocardiography in 1974¹⁹. The main interest since has been the re-evaluation of M-scan echocardiography, developing a valuable technique for the most appropriate planning of invasive studies, and also providing an alternative in those cases where angiocardiology does not provide the answer or is too hazardous for critically ill patients.

CHAPTER I

PHYSICAL PRINCIPLES OF ULTRASOUND

For the echocardiographer a thorough understanding of the physical nature of sound greatly facilitates the understanding of ultrasonic images and may prevent errors in interpretation and enable the operator to optimise the use of this diagnostic technique. In the following chapter the basic physical principles of ultrasound and scanning techniques are explained, which relate to the particular projects of this thesis, and which helped to find different interpretations in many instances. This understanding, which has been accumulated over the years by working with many different methods, assists in identifying such errors in interpretation as may arise due to the result of poor scanning techniques or artefacts. These must be differentiated from the features demonstrating specific conditions of the investigated organs.

The word 'sound' has unfortunately achieved two meanings²⁰, namely subjective and objective sound.

SUBJECTIVE SOUND

The subjective sound is what one hears. This implies that it may differ in quality from one subject to another. A loud shrill sound may for many reasons be less offensive for, and better tolerated by, a young individual spending much time in noisy discotheques than by an elderly person living in a remote country cottage. If sound can be perceived subjectively, there must be a real sound that can be measured objectively, i.e. independantly from individual feelings or emotions. This objective sound, which is dealt with in more depth later, is the originator of the subjective sound, after being received by the external ear and transferred via the middle ear to the inner ear. Here the mechanical signals are transformed into electrical impulses, which are conducted to the brain in order to be finally interpreted subjectively. This complex conversion from objective to subjective sound starts with the ear-drum (tympanic membrane) and ends in the auditory centre of the brain.

OBJECTIVE SOUND

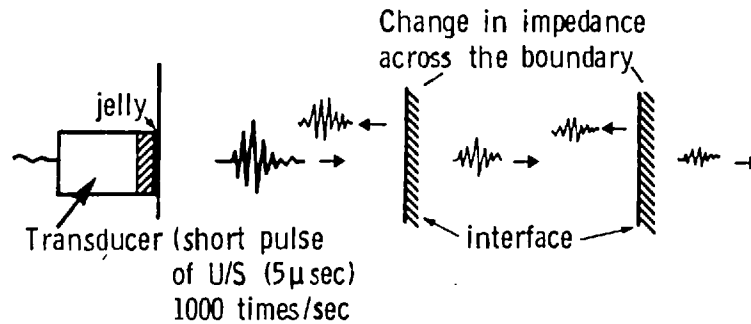
This is a physical phenomenon produced by a vibration of mass within a surrounding medium (solid, liquid or gas). It is a prerequisite that this mass has elasticity, which means that after having been moved out of its resting position, it returns to it after one or several oscillations. To express it differently, any mechanical disturbance which has mass and elasticity produces sound, irrespective of whether somebody hears it, or whether it is audible or not. Thus objective sound is measurable.

Ultrasound by definition is sound above the human audible range, generally accepted to be above 20 000 Hz. In order to measure it one has to understand some of its characteristics. In medical applications where one- and two-dimensional images are required the 'pulse echo technique' is employed. A piezoelectric element, e.g. a crystal such as quartz, or a ceramic such as barium titanate or lead zirconate, is stimulated by an electric impulse of short duration (1-2 microsec.), thus resulting in a contraction and expansion of the element, hence producing a damped ultrasonic oscillation which is transmitted into the tissue under examination. After transmission the transducer is electronically switched to reception mode to await the reflected ultrasound.

In soft tissues the oscillation propagates as a longitudinal pulse wave in the direction of the axis of the transducer at the velocity of sound of the object medium (fig. 1). Discontinuities in the object medium (acoustic interfaces) along this axis are characterised by a change in acoustic impedance which is equal to the product of density (ρ) and sound velocity (v). At each change in acoustic impedance part of the incident ultrasound pulse intensity is reflected and returns to the transducer now in reception mode. The amount of reflection depends on the angle of incidence. For medical ultrasound this simply means that any change in acoustic properties between organs or between structures

ULTRASOUND $\Rightarrow f > 17 \text{ kHz}$ (inaudible to humans)

DIAGNOSTIC FREQUENCY RANGE $\sim 1\text{-}5 \text{ MHz}$



INTERFACE = any organ with different acoustic properties

ACOUSTIC IMPEDANCE = $p \times c$

p = density

c = velocity

Figure 1. Diagrammatical illustration of a pulsed echo pathway through a medium with different acoustic properties. See text.

within one organ produces an interface which is recorded on the oscilloscope.

It is the reflected ultrasound or 'echo' which is displayed in the ultrasound image. Since the velocity of ultrasound in tissue can be measured, the returning echoes can be timed between transmission and reception. Thus acoustic interfaces can be displayed according to their exact distance from the transducer.

Only a few explanations about major physical factors follow, which are essential for critical analysis of the ultrasound images. Further information relating to the physical principles may be obtained elsewhere²¹.

PROPAGATION

Propagation of ultrasound is by way of a mechanical vibration of the molecular particles of the medium under examination in the form of a compression and rarefaction wave motion, as shown later in fig. 3. In soft tissue this is a longitudinal wave and the sound velocity of this wave is determined by the density and elasticity of the medium

(fig. 2.). Thus not mass but energy is transferred along the

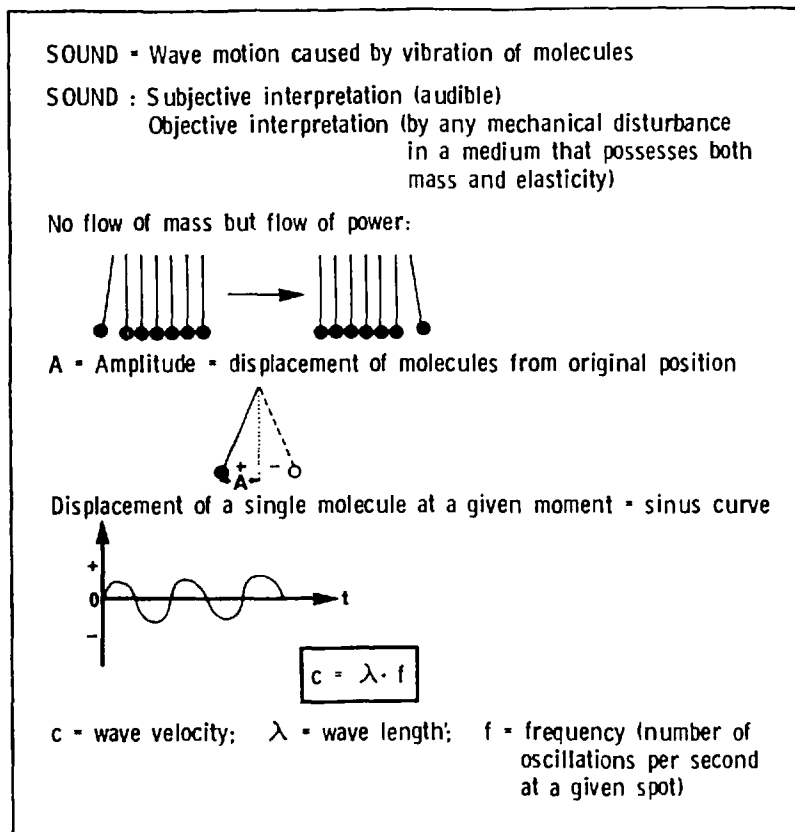


Figure 2. Diagram illustrating the propagation of ultrasound in tissue by means of energy transfer in the direction of sound propagation. See text.

axis of wave propagation, as illustrated by Newton's cradle.

WAVELENGTH

The wavelength (λ), that is the distance between, for example, two successive compression peaks (figs. 2 and 3) is determined by both the transducer oscillation frequency and the sound velocity in the examined medium according to the relationship: $v = \lambda \times f$.

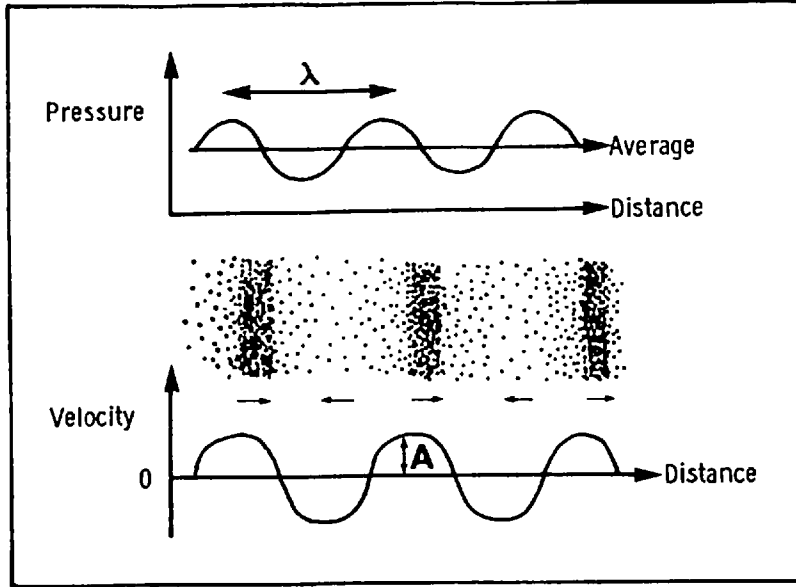


Figure 3. Diagrammatic representation of ultrasonic waves with compression and rarefaction of molecules, and their related pressure and velocity curves.

REFLECTION LAW

Ultraound wave propagation conforms to the basic law: α_E (angle of incidence) = α_R (angle of reflection). Fig. 4 illustrates the law of reflection where the angle of inci-

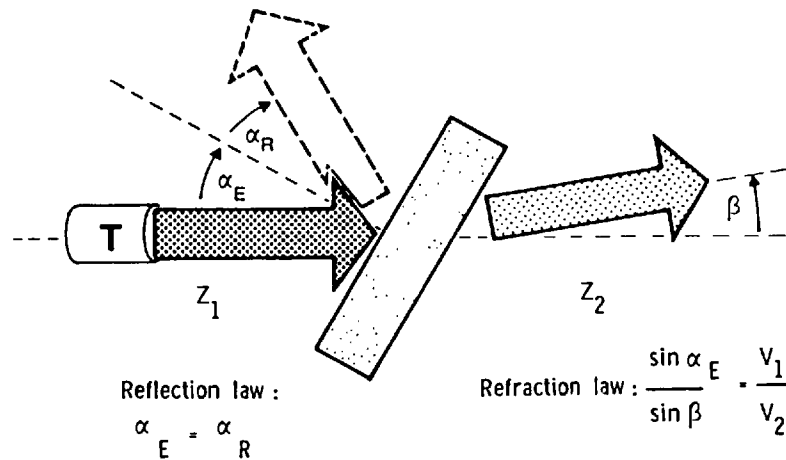


Figure 4. Illustration of reflection and refraction laws (T=transducer, E=emission, R=reflection, $Z_{1,2}$ = acoustic impedance of media 1 and 2, $V_{1,2}$ = velocity in media 1 and 2).

dence (α_E) between the line perpendicular to the target (broken line) and the emitted ultrasonic wave equals the angle between the perpendicular and the reflected wave (α_R). Thus to receive maximum reflection the transducer should be directed perpendicularly to the target.

REFRACTION LAW

The law of refraction is also illustrated in fig. 4 where the angular difference between the line perpendicular to the target (broken line) and the emitted ultrasonic wave in medium 1 (Z_1) and the angle between the perpendicular and the refracted wave in medium 2 (Z_2) is directly proportional to the difference in sound velocities V_1 and V_2 of the two media. For the purpose of the physical argument, the acoustic interface of the target in the diagrams has to be understood as a plane and not as a medium in itself.

To facilitate the understanding of the reflection laws, the target surface (interface) is assumed to be a flat plane surface. However, in reality the interface can be quite irregular, as indicated in fig. 5.

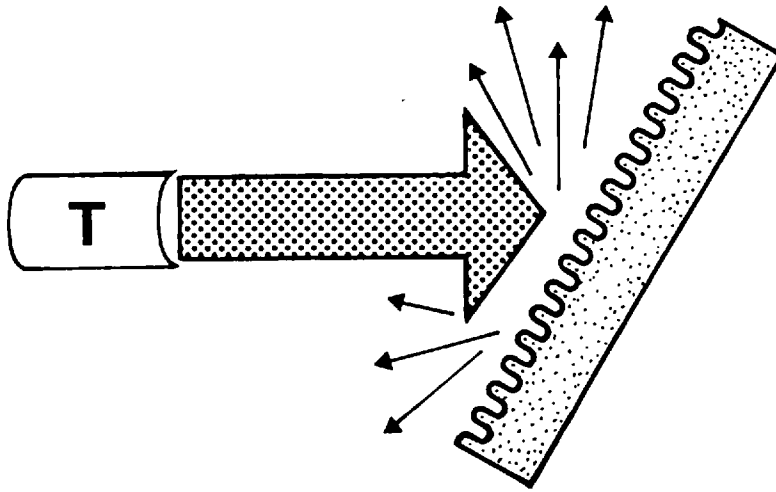


Figure 5 illustrates the scattering phenomenon of ultrasonic waves when reflected from an irregular target surface.

Therefore some echoes will be received even if the transducer is not precisely perpendicular to the main tissue axis under examination. This phenomenon is due to the 'scatter' of the ultrasound beam at the irregular target surface. An example is given in the chapter on 'Hypertrophic Cardiomyopathy' where the malalignment of myocardial fibres produces such a scattering phenomenon, resulting in relative damping of myocardial echostructures in the septal bulge (p.132).

Fig. 6 illustrates a perfect example of optimal reflection.

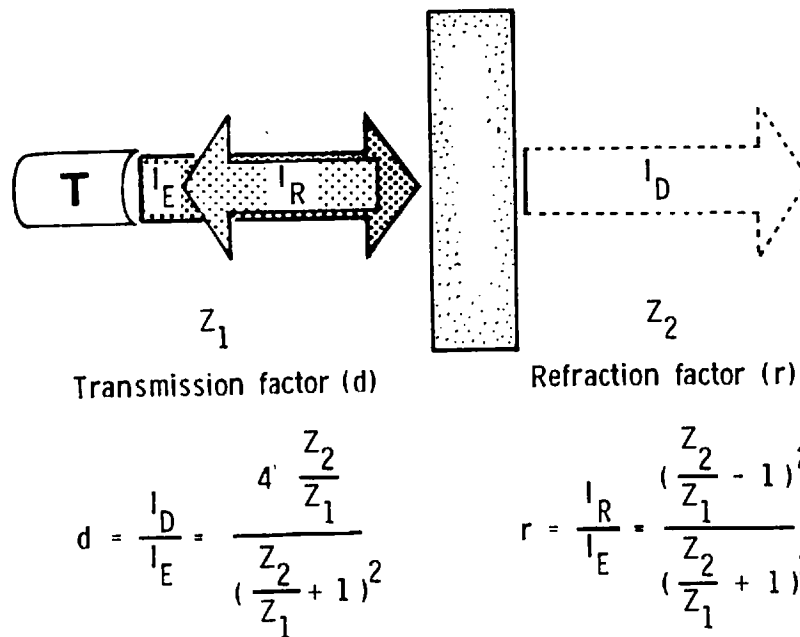


Figure 6. Conversion of acoustic power when ultrasound waves hit a target (acoustic interface) perpendicular to its surface. For further detail see text and fig. 4.

The reflection factor (r) and the transmission factor (d) describe the fractions of reflected and transmitted intensity (I) for an ultrasound wave which is perpendicular to an interface. It can be seen from the above formulae that r and d are functions of the acoustic impedance. The greater the impedance difference between the two media Z_1 and Z_2 , the more energy is reflected, thus allowing less of the original energy to penetrate further. Very strong reflections are received from great acoustic impedance differences, such

as tissue/gas or tissue/bone. This accounts for the relative limitations in the application of ultrasound in medical examinations.

ATTENUATION

Attenuation of the emitted ultrasonic wave occurs as it travels through a medium under examination. Although it is a complex phenomenon it may be understood from three main contributing mechanisms:

1. DIVERGENCE of the initially parallel beam with increasing penetration leading to a reduced ultrasound intensity per unit area.
2. SCATTER caused by energy reflected in directions other than along the axis of the ultrasound beam, resulting in less energy available for image production.
3. ABSORPTION, itself a complex phenomenon, which may be regarded as the conversion of kinetic energy of the oscillating particles into a form of thermal energy as a result of friction.

The attenuation or loss of energy with increasing depth is compensated for on the ultrasonic scanners by introducing a depth/gain compensation control.

RESOLUTION

The two forms of resolution of importance are:

1. axial resolution
2. lateral resolution.

Axial resolution

This is the ability to resolve targets along the axis of the ultrasonic beam. It depends firstly on the wavelength (λ), since only points larger than $\frac{1}{4}$ of the wavelength can be differentiated²¹, and secondly on the pulse duration.

Since the pulse duration is fixed with most equipment, an improvement in axial resolution can be achieved by using a higher frequency transducer with a correspondingly shorter wavelength. However, in practice the spot-size of the display screen is the overriding limitation of actual or perceivable axial resolution, which may generally be at best only in the order of 0.5 mm. Although an increase in frequency provides a higher resolution, the advantage is offset by a reduction in penetration.

Lateral resolution

Lateral resolution is the ability to resolve targets adjacent or parallel to the beam direction. It is mainly influenced by beam width, which is itself determined by the following factors:

1. transducer size,
2. transducer frequency,
3. transducer shape (focussed or collimated transducer),
4. depth of investigated structure.

CHAPTER II

EQUIPMENT

The main equipment with which the one- and two-dimensional images of this thesis were obtained is described in this chapter.

A. TIME-MOTION SCANNER 'EKOLINE 20'

The strip-chart M-scans in this thesis were obtained with the 'Ekoline 20' ultrasonoscope from Smith Kline Instrument Co.Ltd., England, which was attached to a Cambridge strip-chart recorder. The equipment consists of a pulse generator, a transmitting and receiving transducer, a signal amplifier, a cathode ray tube display (oscilloscope), and a Polaroid camera. Ultrasonic waves are emitted from a focussed 2.25 MHz single transducer with a repetition rate of 1000 pulses per second, and are reflected from any acoustic interface on their pathway. The pulse echoes are transformed into electrical signals which can be seen on the oscilloscope, photographed by Polaroid, or observed and recorded on the Cambridge strip-chart recorder. An electrocardiogram was always simultaneously recorded on the M-scan echocardiograms.

MULTICHANNEL RECORDER (CAMBRIDGE INSTRUMENTS Inc.)

For some of our initial strip-chart M-scan recordings we used the 6-channel recorder type 72 112 together with the Echoscan Converter type SN8634. In some cases phonocardiograms were simultaneously recorded using the Cambridge suction microphone type 5-3643 with the amplifier type 72352. The electrocardiogram was recorded via the ECG module type 72362. The combined M-scan tracings were recorded on photographic paper, initially 5 inches wide, and later 7 inches wide with the 12-channel recorder type 01007.

B. PICKER ECHOVIEW IV LAMINOGRAPH

The echoview IV Laminograph is a conventional B-scan

machine. It consists of the main box housing the electronics, the storage scope, and an additional slave oscilloscope (for the simultaneous display of the echo-pattern in A-mode), and a separate electro-mechanical gantry which is important for accurate transmission of position and direction of the 2.25 MHz ultrasonic probe onto the screen. A commercially available ECG trigger device was included, allowing ultrasonic pulses to be emitted for 10 msec. during each cardiac cycle, the emission being actuated electronically and triggered by the R-wave of the electrocardiogram, which must be monitored simultaneously. A built-in delay control allows the emission burst, the gate, to be chosen at any preselected phase of the cardiac cycle. The timing of this short emission is shown as a time-marker line on a displayed electrocardiogram, as well as on all structures of the mitral echogram (M-scan) obtained as a preliminary to the triggered B-scan (see fig.57, p.81, later). Further details will be described in connection with the scanning methods in chapter VII, p. 75.

C. MECHANICAL LINEAR REAL-TIME B-SCANNER 'VIDOSON'

This B-scan unit consists of an ultrasound applicator (see fig.7), a monitor box housing all the electronics, a

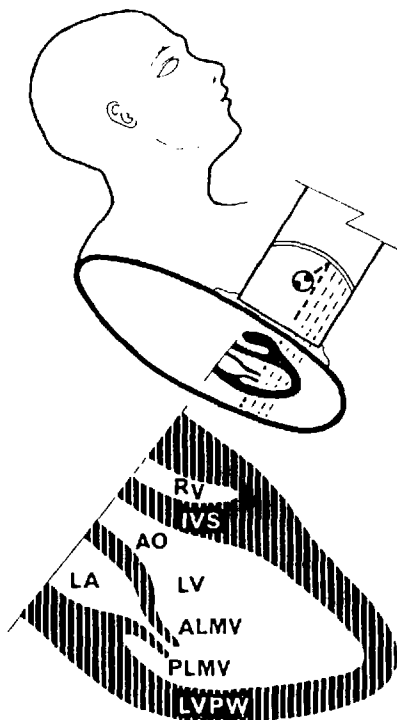


Figure 7. Diagrammatical representation of the principle of the linear real-time B-scanner, the Siemens 'Vidoson', the cross-sectional plane through the thorax, and the corresponding anatomical orientation on the B-scan in the lower panel. (RV=right ventricle, IVS=interventricular septum, Ao= aortic root, LA= left atrium, LV= left ventricle, ALMV+PLMV=anterior+posterior leaflet of the mitral valve, LVPW=left ventricular posterior wall).

stand, and an easily adjustable gantry to move the applicator, mounted on a mobile trolley. The applicator houses a pair of

2.5 MHz transducers, fixed opposite each other on a support which rotates inside a waterbath containing a stationary parabolic mirror system. Only the transducer facing the concavity of the mirror emits ultrasound pulses of about 1 microsecond duration, and at a repetition rate of about 2000 per second. The transducers operate in the focal line of the parabolic mirror system, and thus the ultrasonic beam is swept through the coupled tissue in parallel linear fashion. The echoes return along the same pathway as the transmitted pulses. Because of the relative slow rotation speed of the transmitter support (8 times per second), the spatial line shift between the emitted and received pulse echoes is negligible. Since two transducers are operating, images are displayed on the cathode ray tube at a frame rate of 16 per second.

In the initial phase of evaluating this machine for routine use in cardiology, only a Polaroid camera and a single lens reflex camera for 35 mm films were available, and it was not possible at that time to record an ECG simultaneously. Subsequently cardiac events were timed by simultaneously recording the B-scan screen (see F in fig. 8) and an electro-

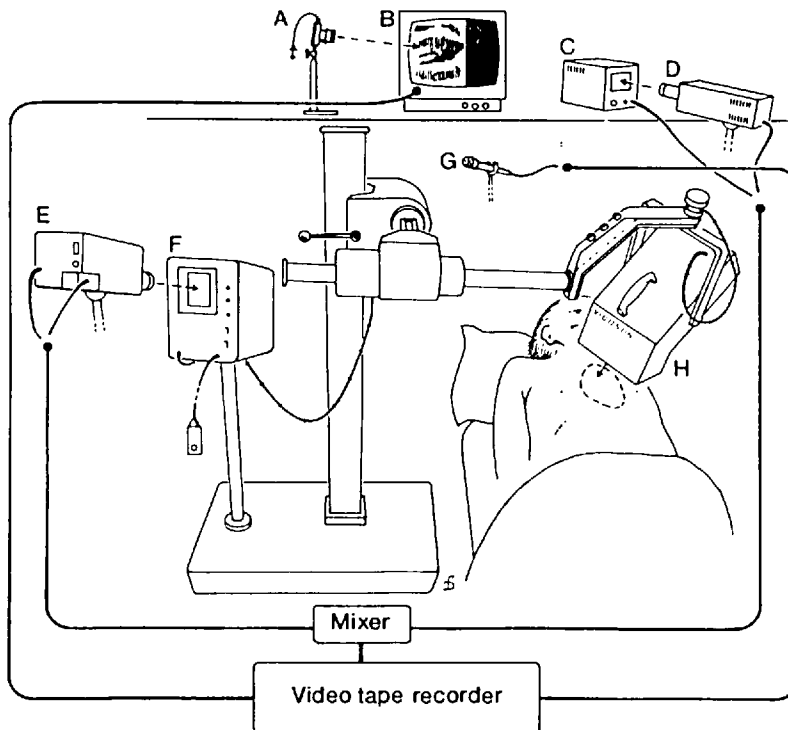


Figure 8.
Diagram showing the modifications used with the linear real-time B-scanner to record B-scans and electrocardiograms simultaneously. For further orientation see text.

cardiogram (Sirecust BS 1, see B in fig. 8) by means of two television cameras (Siemens K2B, see D and E in fig. 8) and a video tape recorder (Sirecord). The combined images are displayed on a television monitor (B in fig. 8) during the B-scanning procedure, and a microphone (G in fig. 8) allows comments on the B-scan findings to be stored simultaneously on the sound track of the video tape. For documentation and precise analysis these combined images are replayed at normal speed, variable slow motion, or as single frames, and then photographed (A in fig. 8) accordingly from the television monitor (B in fig. 8) on Ilford FP4 or Pan F 35 mm films. The exposure time is set at 0.5 sec. and the lens aperture between f16 and f22. Recently better results were obtained with an automatic camera, the OM II Olympus.

D. ELECTROSCAN OR PHASED-ARRAY SECTOR SCANNER TOSHIBA SSH-10A

This scanner consists of a box housing the electronics and two cathode ray tube screens, one of which serves as a storage tube. The ultrasonic probe consists of an array of 32 small 2.4 MHz transducers, producing a 78° electronically swept sector real-time B-scan with a diagnostic depth of up to 20 cm. The sector image may be composed of 112 or 224 lines. Two lines within the sector may be chosen to display the corresponding M-mode scans simultaneously on a storage oscilloscope or any attached strip-chart recorder. Four channels are provided to display an electrocardiogram, a phonocardiogram, carotid, or apex pulse curve. Patient's identity and a digital caliper read out may be stored permanently on the cathode ray tube during the whole time of the examination, a most valuable facility for the identification of records. In addition the ultrasound echoes may also be displayed in A-mode or in two dimensions as a kymogram, which is identical to what is referred to in this thesis as continuous sweep technique in B-scanning (p. 71).

This equipment was given to us for evaluation by courtesy of Oldelft Deltronix Ltd., Den Haag/Holland. At that time

only Polaroid recording was available.

CHAPTER III

DISPLAY MODES AND IMAGE CONSTRUCTION

A. DISPLAY MODES

Reflected ultrasonic waves which return to the emitting transducer are transformed by the piezo-electric elements into electrical signals. These can be displayed on a cathode ray tube (CRT) in different modes.

1. A-mode

A-mode stands for amplitude modulation, as the acoustic interfaces are displayed as amplitudes along the base line of the CRT (see fig 9).

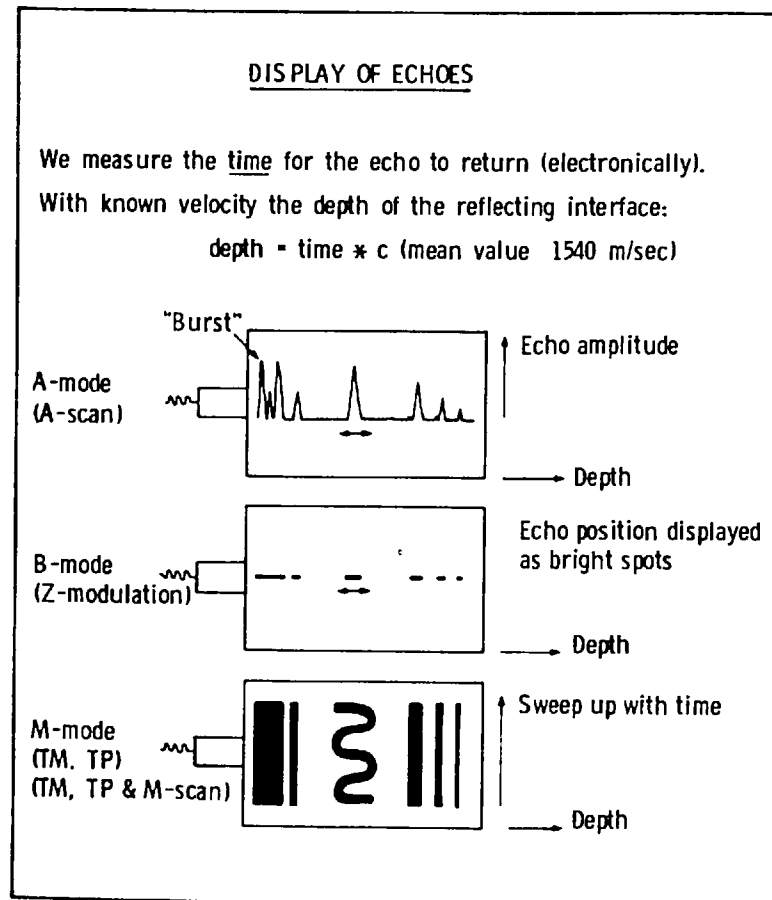


Figure 9. Display modes of ultrasonic waves on a cathode ray tube (c=velocity of sound in tissue, TM= time motion, TP= time position, M= motion).

Manufacturers of ultrasonic equipment have universally

agreed upon a mean value of ultrasound velocity in tissue (about 1540 m per second). Therefore one is able to determine the depth of the acoustic interfaces by measuring the time for the echoes to return. The first amplitude to appear on the CRT (fig. 9) is the 'opening burst', produced by the interface between the transducer and the complex of contact jelly and skin surface of the patient. All subsequent amplitudes give a representation of the depth of the various acoustic interfaces along the ultrasonic beam. Static boundaries such as the chestwall, produce static amplitudes on the CRT, whereas moving structures, such as valves and walls of the heart, are represented by amplitudes moving along the time base. The intensity of the reflection at any interface is proportional to the height of the pulse amplitude. The larger the amplitude, the wider it is at the time base, and thus this width can also be taken as a measure of the intensity. Therefore two dimensions can be measured:

1. depth of reflecting interfaces and
2. echo amplitude.

The depth is measured along the direction of the ultrasonic beam, which represents a spatial dimension within the investigated tissue. The echo amplitude can also be measured, but it represents intensity, and not a spatial dimension in relation to the tissue, since it is measured in a direction different from that of the ultrasonic beam (see fig. 10 later), and in different units. Therefore A-mode is regarded spatially as a one-dimensional method.

2. B-mode

The A-mode technique has not been found to be particularly useful for the display of moving heart structures. For this purpose the brightness-modulation (B-mode, or Z-mode as referred to in radar techniques) is used, whereby the acoustic interfaces are displayed as bright spots or streaks along the time base, depending on the intensity of the echoes (fig. 9, middle). The B-mode spots represent the base of the

corresponding A-mode amplitudes. The higher the intensity, the larger are the amplitudes and the wider are the bright spots or streaks in B-mode.

3. T/M-, T/P-, or M-mode

T/M stands for time-motion, T/P for time-position, and M for motion. In M-mode the brightness modulation or B-mode display is swept up electronically with a constant velocity on a CRT, on Polaroid paper, or on a strip-chart recorder (fig. 9, lower panel). Thus the static spots of the brightness modulation will appear with the after-glow transiently on the CRT, or permanently on a storage oscilloscope, as thin or wide straight lines, and the moving interfaces as thin or wider curves, depending on the intensity of ultrasound reflection at the acoustic interfaces (fig. 9, lower panel).

B. IMAGE CONSTRUCTION

1. A-scan

When the echo-screen displaying the A-mode is photographed, an A-scan is obtained. Thus the A-scan echo amplitude is displayed as a function of distance of the reflecting interface at the particular moment the picture is taken. This method is particularly useful to look at non-moving structures. It has therefore extensively been used in neurology to measure the extent of mid-line shifts in patients with space occupying lesions in the brain²² and is still used as the ultrasonic technique of choice for particular situations in ophthalmology.²³

2. T/M-, T/P-, or M-scan

In order to obtain a record from the M-mode display on

the CRT, different methods can be employed. One can either move the B-mode display during recording across a storage tube or static Polaroid film, or one can move a film or photosensitive paper (photographic or ultraviolet paper) past the stationary B-mode display. This mode of recording was used to produce our M-scan echographic records by interfacing the Ekoline via a module with a Cambridge strip-chart recorder (see p.19). Some scans in this thesis have been produced by recording the M-mode display directly on Polaroid films or by photographing the storage tube of the Echoview IV Laminograph in the same way. The corresponding recordings are referred to as T/M-, T/P-, or just M-scans. The latter expression will subsequently be used in this thesis.

3. B-scan

Photographing the B-mode display from a screen does not produce a B-scan. The B-mode itself is not used for measurements, but is employed to build up both time-motion scans and B-scans.

No matter at what angle the transducer is directed in M-scanning, the reflected sound waves are always displayed in B-mode along the horizontal base line of the oscilloscope (fig. 9, middle, and fig. 10, left). In the B-scan technique (fig. 10, middle) the time base of the brightness modulation is displayed according to the direction and position of the transducer orientation in space, and may be stored, if so desired, on a storage CRT. Thus in addition to the width or horizontal distance (x), another spatial dimension, the height (y), is introduced. By compounding convergent and divergent scans (hence the name 'compound B-scan') and thus displaying the reflected ultrasound waves from different directions on the storage oscilloscope, a two-dimensional cross-sectional image may be built up in a plane prescribed by the gantry holding the transducer (fig. 10, right below). For the precise transference of the position of the transducer to the

'B' -scan

'B' -scan is a two-dimensional cross sectional image built up in a given plane using the B-mode display on a storage scope.

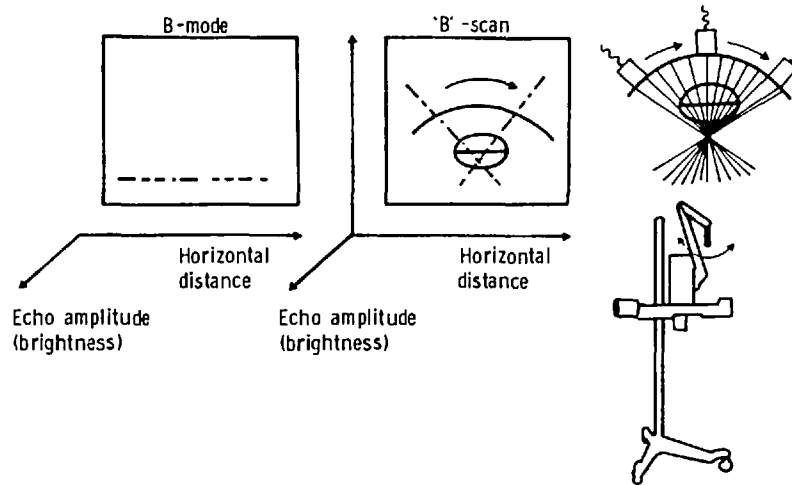


Figure 10. Diagrammatical illustration of the spatial dimensions involved in B-mode and B-scans. See text for further information.

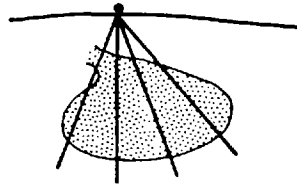
oscilloscope, a complicated electro-mechanical gantry is required, which considerably adds to the cost of B-scan equipment. The brightness (z), strictly not a spatial dimension, is directed towards the observer's eye and may give the impression of depth when displayed on a CRT. Such an oscilloscope is no longer bi-stable, and usually enables about 10 to 16 different brightness levels or grey tones to be differentiated (so-called 'grey-scale'). This dimension (z), however, cannot be measured quantitatively. Thus B-scan is referred to spatially as a two-dimensional echo-method, which allows a quantitative assessment of dimensions in any direction within a given cross-sectional plane.

Two-dimensional or B-scan imaging of the heart can be accomplished with different techniques and equipment. All scanning equipment uses the B-mode display to construct a 2-dimensional image with the cross-sectional scan. This can be accomplished by using the B-mode as a sector scan, as a

compound sector scan, or a parallel or linear scan, as illustrated in fig. 11.

SECTOR-SCAN

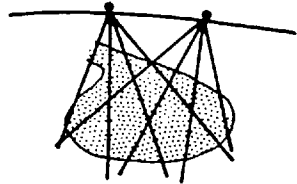
CST
Electroscan
Mechanical rocker



Many angles from
one position

COMPOUND SECTOR-SCAN

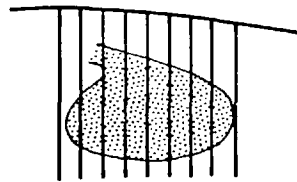
Triggered B-scan



Many angles from
more than one
position

LINEAR

Vidoson
Multiscan



Single angle from
many positions

Figure 11. Diagrammatical illustration of beam direction in sector, compound sector, and linear scans. CST=continuous sweep technique. For further information see text.

In a sector scan the ultrasonic beam is angled from one transducer position in many different directions within a given scanning plane. A compound sector scan consists of two or more sector scans, carried out at different locations within a pre-selected scanning plane. A linear scan is achieved by employing many B-mode lines with the same angle of incidence but originating from many different transducer positions. As will be seen later, the sector scan technique is employed with the continuous sweep technique, with the electroscan, and with the mechanical rocker. In cardiology the compound sector scan method is usually used for triggered B-scanning, although a single sector scan can also be obtained by carrying out a simple triggered sector scan from one intercostal space only. The linear B-scan principle is made use of with the mechanical real-time B-scanner, the 'Vidoson', and with the linear multi-element systems.

CHAPTER IV

REVIEW OF PRESENTLY AVAILABLE TWO-DIMENSIONAL SCANNING TECHNIQUES

The purpose of reviewing the various available B-scanning techniques and showing an example of a scan obtained by each method is to provide an understanding of the particular techniques used and the scans upon which this thesis is based.

Three main kinds of two-dimensional scanning methods can presently be used for diagnostic purposes in cardiology, as summarised and grouped in fig. 12.

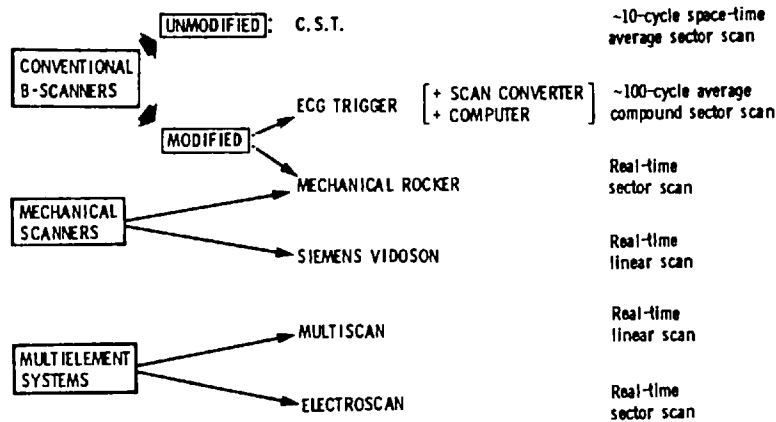


Figure 12. Diagrammatical review of presently available two-dimensional ultrasound scanning systems. (CST=continuous sweep technique).

There are the conventional or compound B-scanners, mainly used in obstetrics and gastroenterology, then the mechanical B-scanners, and finally the multi-element systems, both equally used in cardiology, obstetrics, and internal medicine.

A. CONVENTIONAL OR COMPOUND B-SCANNER

The conventional B-scanners can be used as in obstetrics or gastroenterology, or modified to suit the requirements of cardiac imaging.

1. Unmodified compound B-scanners

If one uses the compound B-scanners on the heart in

exactly the same way as for example on the liver or a foetus, then we prefer to call this method:

a. Conventional B-scanning (CBS) technique

Fig. 13 indicates that the single transducer of a com-

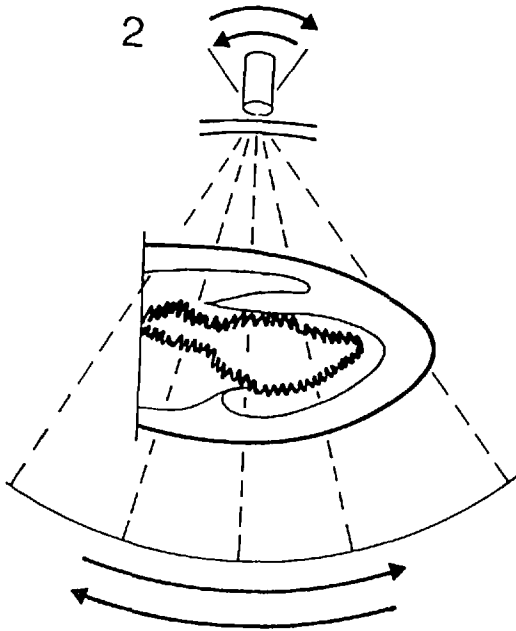


Figure 13. Diagrammatical illustration of the conventional B-scan technique on the heart and a resultant scan in the long axis plane. For comparison see fig. 14.

compound B-scanner is placed on the chestwall, and the cross-sectional scanning plane goes through the long axis of the heart. The anatomical details are described in chapter V, 'Anatomical Orientation in Echocardiography', p.49. The transducer may be moved to and fro as a sector in the pre-determined scanning plane from one intercostal space only, or the transducer may even be moved to another position within the plane to carry out a compound sector scan. This technique is not very satisfactory for imaging the heart, because motions of heart structures

produce blurred images in which echoes obtained in diastole are superimposed with adjacent echoes obtained in systole. One can therefore scan long enough until all space between the end-diastolic and end-systolic positions of the heart wall is imaged, so that the constant overwriting finally results, as seen in fig. 14, in an echo free space, which roughly represents the end-systolic cross-sectional area of the left ventricle. This technique will be dealt with in more depth in chapter VI, p.66.

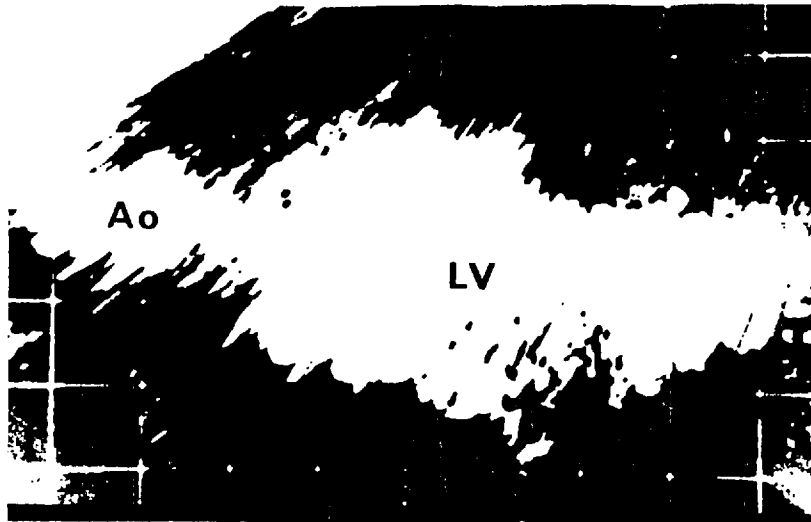


Figure 14. A virtual end-diastolic long axis frame of a conventional B-scan of the heart. This is achieved by multiple sweeps which finally blur the phases of end-systole and end-diastole.

b. Continuous Sweep Technique (CST)

As with the conventional B-scanning technique this was also a byproduct discovered when trying to find an appropriate scanning plane for triggered B-scanning without losing too much time. The transducer was placed on the chestwall, on the presumed longitudinal axis of the heart, as indicated in fig. 15, and then a single continuous

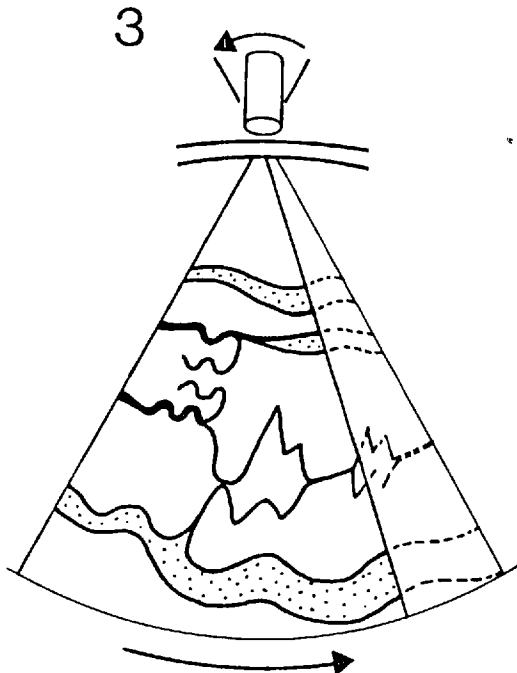


Figure 15. Diagrammatical representation of the Continuous Sweep Technique and the resultant combination of an M- and B-scan echogram of the heart. See text for further information.

sweep was carried out with continuous registration on the storage tube. Thus it became obvious that structural details and their motion could be recognised as on M-scans, however, with exact anatomical relationships in two dimensions, i.e. retaining the actual shape of the left ventricular cavity. In order to distinguish this scanning technique from the manually carried out Continuous Sweep Technique in M-scanning, it is described as 'Continuous Sweep Technique in B-scanning', to stress the manual character of both methods. An example of such a scan is given in fig. 16.

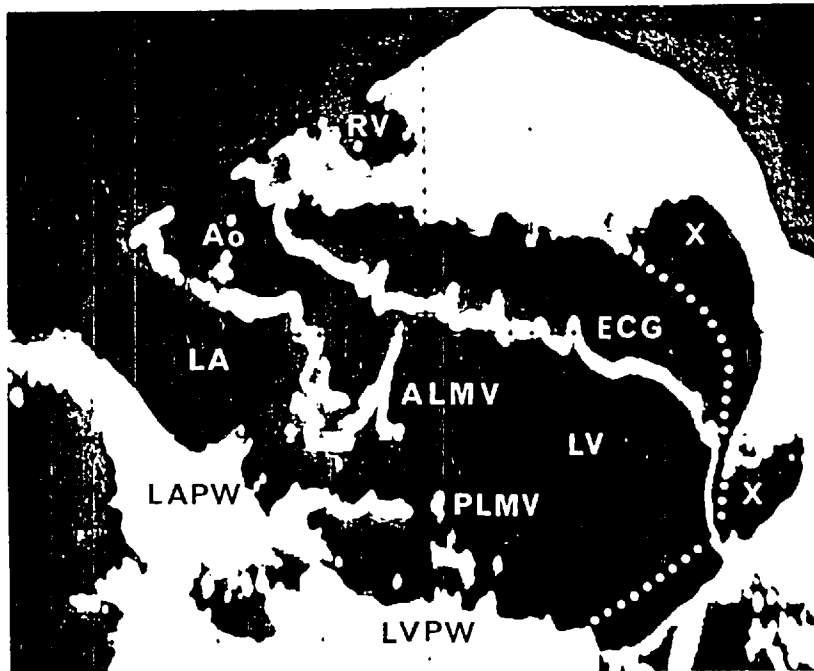


Figure 16. Two-dimensional image of a normal heart recorded with the Continuous Sweep Technique, which enables one to appreciate wall motions and exact anatomical relationships in a pre-determined cross-sectional plane. For orientation see later Fig. 53 p. 69. The displayed electrocardiogram (ECG) gives an indication of the time taken to carry out the sweep.

If one wants to record the ECG as well with this technique it has to be positioned in the left ventricular cavity where it cannot interfere with cardiac structures. Six QRS complexes are thus recorded, starting between the aortic walls and continuing through the left ventricular outflow tract towards the apex. The details will be described in chapter V, 'Anatomical Orientation in Echocardiography', p. 49, and in chapter VI B, 'Continuous Sweep Technique', p. 71.

2. Modified compound B-scanner

a. Triggered B-scan

In order to overcome the inevitable blurring of images, with the use of conventional B-scanners on a rapidly moving organ such as the heart, these scanners can be modified for visualising cardiac anatomy at any desired instant of the cardiac cycle. This is accomplished by introducing an ECG trigger device which allows ultrasound pulses to be emitted for only a short fraction of a second during each heart period. Thus one B-mode line is recorded on the storage tube during each cycle and describes only a small part of the scan. The compounding of about 90 to 120 such lines (fig. 17), by moving the transducer a fraction of an angle after each cardiac cycle in a given plane (from aortic root

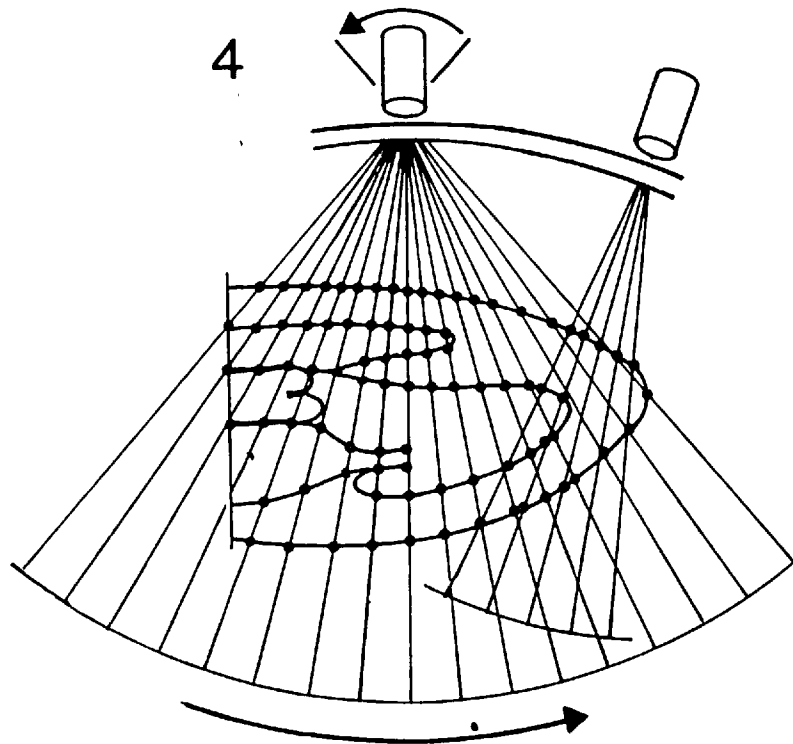


Figure 17. Diagrammatical representation of the triggered B-scan technique indicating that the transducer may also be moved to a different intercostal space in the pre-determined cross-sectional plane.

to the cardiac apex or vice versa), enables a 'stop-action' or 'stop-motion' scan to be built up. The completion of such a scan takes about 1 to 2 minutes, depending on the heart rate of the patient. Thus the triggered B-scan, as shown in an example in fig. 19, p. 38, represents an average value of a pre-determined phase of the heart as compared with a still frame from a real-time B-scan display on video tape or film (see fig. 26, p.43). The anatomical details will be discussed in greater depth in chapters V and VI, pp.49 and 66.

b. Scan converter display

A scan converter is a device which enables the ultrasonic images to be stored with grey scale information. However, the image is not visible but stored electronically in either digital or analogue mode, and must be read off electronically for visual display on a television monitor. With the Cardio-niner from Unirad Co., which employs such a scan converter, frames of 9 different phases of the cardiac cycle are displayed on the screen, after having completed one triggered B-scan at any pre-determined moment of the cardiac cycle. An example is shown in fig. 18. The 9 frames, however,

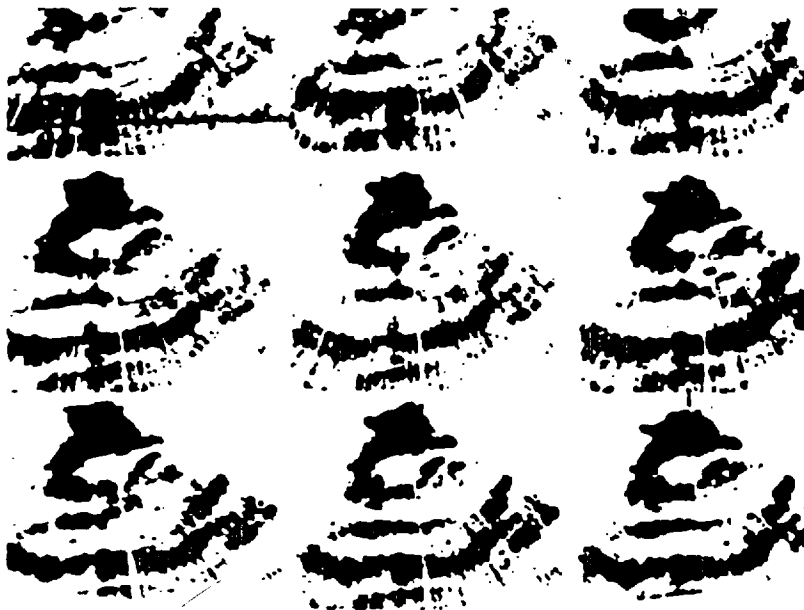


Figure 18. Nine phases of a cardiac cycle displayed on the Cardio-niner (Unirad) triggered B-scan, using a scan converter tube.

are displayed on 1/9th of the area of the screen, and although each of them can be zoomed to full screen size, the resolution does not increase with this manoeuvre (fig.19).

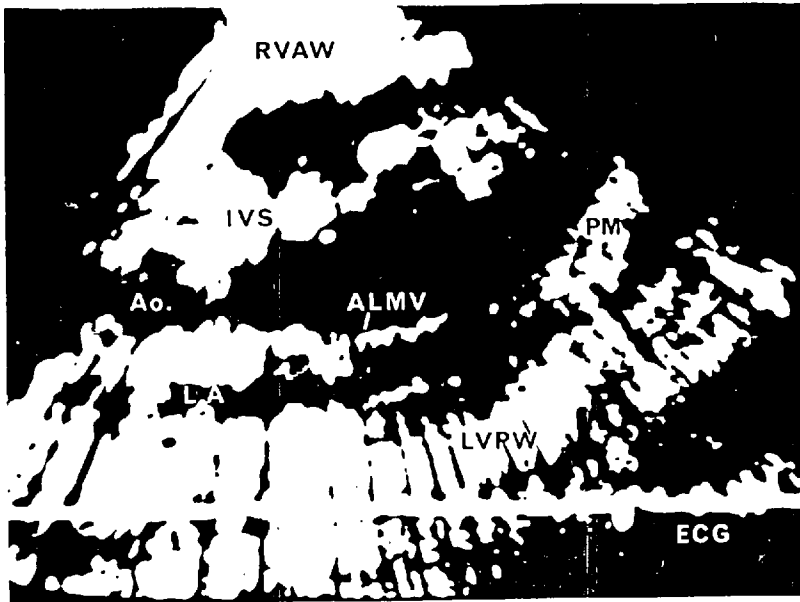


Figure 19.
A single phase of
the 9 triggered B-
scans in fig. 18
zoomed to full
screen size.

The electronic inversion from positive to negative display is an interesting facility but does not add to the information of the patients' condition (fig. 20). These pictures have been taken by myself at a conference and are therefore not representative of the quality one can obtain with this system under appropriate conditions.

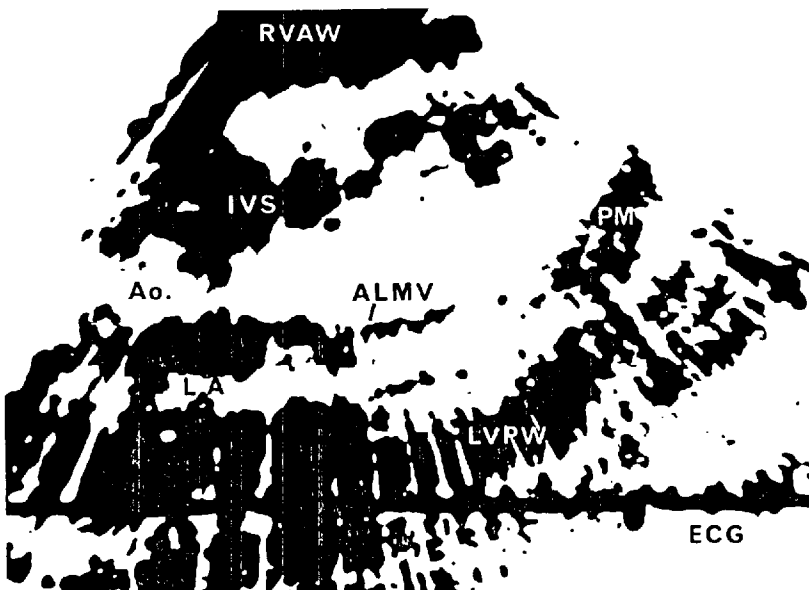


Figure 20.
Electronic inversion
of fig. 19 changes
black into white
and vice versa but
does not add to the
anatomical informa-
tion previously ob-
tained.

c. Computer display

Another possibility for displaying more than one phase of the cardiac cycle is to use a computer to assemble at 45 different phases of each cycle. Work in this field has been shared with our department of Medical Physics at Hammersmith Hospital, using an HP2100 computer.²⁴ Thus 45 different phases are displayed as digitised B-scans, after one complete triggered B-scan was recorded on the storage screen.

B. MECHANICAL B-SCANNER

As indicated in fig. 12, real-time B-scan images can be obtained by modifying the conventional B-scanner in such a way that a single probe or transmitter can be used. Thus they represent a link between the conventional B-scanner and the mechanical real-time B-scanner.

1. Mechanical sector real-time B-scanner (mechanical rocker)

The mechanical rocker (fig. 21) or mechanical sector real-time B-scanner employs a single ultrasonic probe which is no longer angled manually but mechanically to sweep the ultrasonic beam as a sector. The reverse was first achieved by Olofson²⁵ and applied

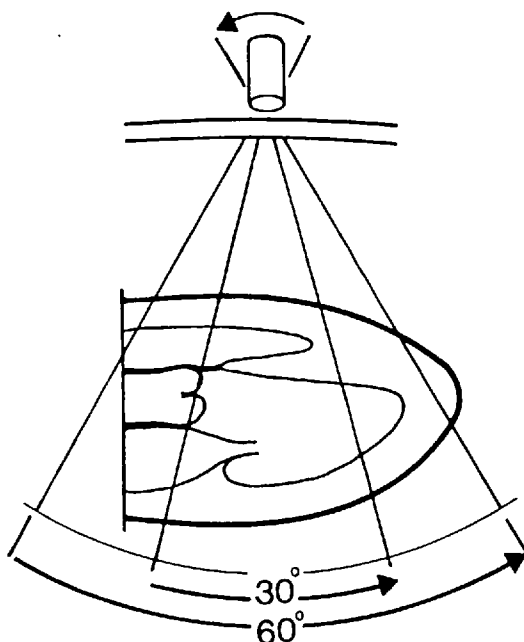
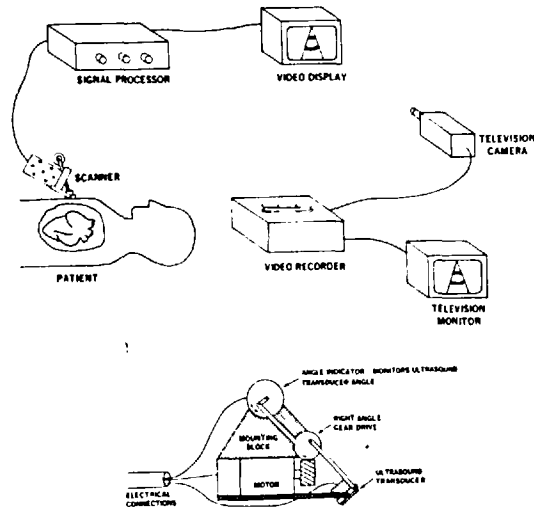


Figure 21. Diagrammatic representation of the mechanical sector scan method, where a single probe is rocked mechanically to produce a two-dimensional real-time sector image of different sizes.

by Asberg in 1967²⁶ by using a rocking mirror system within a water bath, thus producing a mechanical sector scan. The image production rate of 7 frames per second, however, was too slow for satisfactory cine film recordings. Kikuchi et al.²⁷ applied a mechanical real-time sector scanner to the heart already in 1968, which was used in conjunction with a water bath. More recently, Griffith and Henry²⁸ have introduced a more successful modified mechanical sector scanning system. A single ultrasonic probe is continuously moved through a 30° sector at a rate of 15 cycles per second, using a small DC motor and a crank and lever system (fig. 22).



Griffith et al. C. June, 1974

Figure 22. Diagrammatical illustration of the mechanical sector scanner and the corresponding recording method. (From Griffith et al., Circulation, 49, 1147, 1974).

Each complete cycle results in the generation of two 30° sectors, providing 30 separate frames per second. The 12 mm diameter transducer gives good quality images and the sector generation rate is fast enough to prevent flicker on the oscilloscope. The real-time motion pictures can be stored

on video tape and and replayed at will. Fig. 23 gives an example of a still frame in systole and diastole, obtained

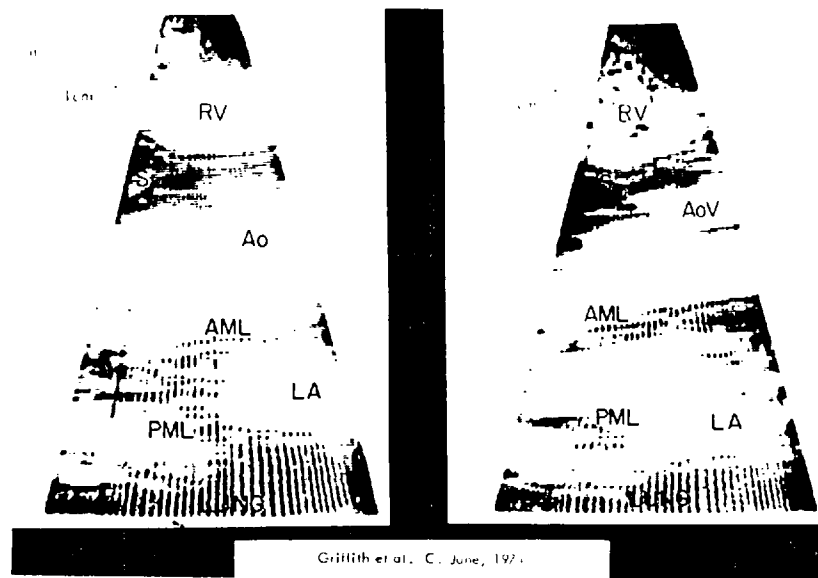


Figure 23. Example of a systolic and diastolic frames obtained with a mechanical sector scanner. (RV=right ventricle, Ao=aortic root, AML=anterior mitral leaflet, LA=left atrium). (From Griffith et al., see reference 24).

with such a scanner. These systems have certain advantages over the multi-element system. By employing a larger transducer, one achieves a greater sensitivity and resolution than with the multiscan system and its small transducer. The increased number of data lines (66 initially against 40 in the earlier multiscan system²⁸) produces images of improved detail. The system is designed to function from a small spot in the intercostal space so that the signal absorption and distortion that may occur when the transducers are placed over the ribs and lung are minimised. These advantages, however, have been gained with some sacrifice. Only a small region of the heart can be visualised and this decreases as one gets near the chestwall and the apex of the sector. With increasing depth and angle of the sector, the lateral resolution in these systems must decline. A number of workers have used this system for clinical investigation^{29,30}, and

different technical solutions have been found to use multiple transducers with small applicators, as indicated in fig. 24.

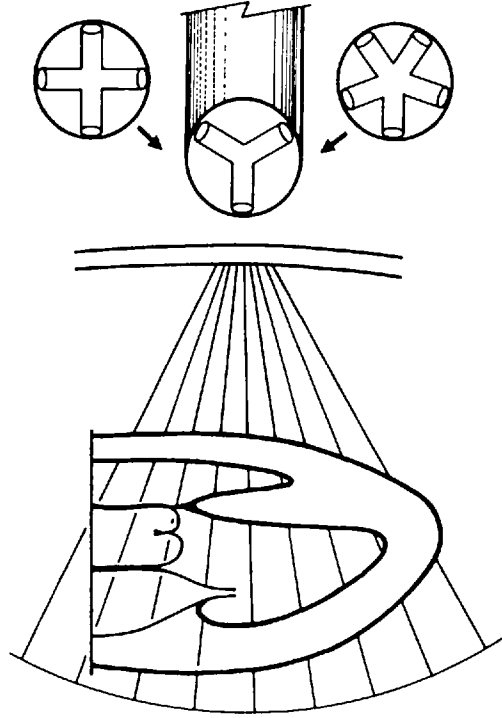


Figure 24. Diagrammatical representation of a mechanical real-time sector scanner employing 3 to 5 rotating ultrasonic probes.

We have had no opportunity to use such real-time sector scanners routinely at Hammersmith Hospital and concentrated on the evaluation of another real-time B-scanner, the Siemens 'Vidoson'.

2. Mechanical linear real-time B-scan (mirror reflector)

The 'Vidoson' system is a linear real-time B-scanner. The linear sweep is achieved by reflecting the ultrasonic beam from two (recently from three) rotating single transducers via a parabolic mirror system within a water bath (fig. 25).

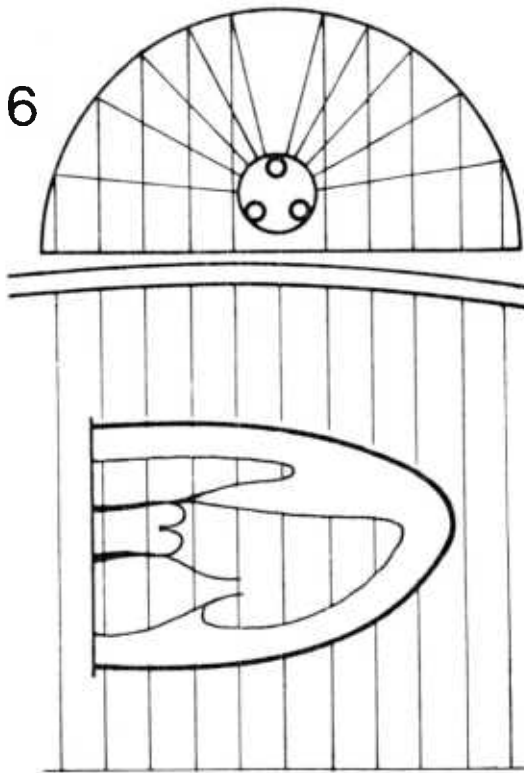


Figure 25. Diagrammatical representation of the mechanical real-time B-scanner, the Siemens 'Vidoson'. Two or three transducers are rotating in the focal plane of a mirror reflector system in a water bath, so that all beams are reflected in parallel linear manner.

Thus linear two-dimensional real-time images may be obtained with a width of 14-16 cm and a depth of up to 20 cm, which allows the entire heart to be appreciated in a longitudinal cross-section (fig. 26) even in grossly dilated or hypertrophied ventricles.

This mechanical linear real-time B-scanner will be dealt

with at length in chapter V, 'Anatomical orientation in echocardiography, p.49 , and in chapter X, p.118.

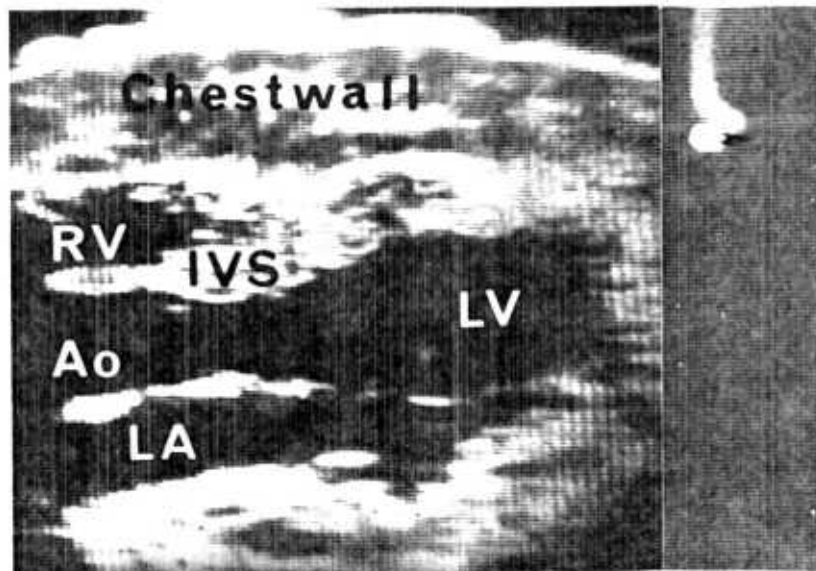


Figure 26. Mechanical linear real-time B-scan from a normal individual in the standard long axis cross-section. (RV=right ventricle, IVS=interventricular septum, Ao=aortic root, LA=left atrium).

C. MULTI-ELEMENT SYSTEM

Among the multi-element systems employing multiple transducers in a linear array, one can again differentiate between linear and sector scanners (see fig. 12).

1. Multi-scan system

The multi-scan is a linear multi-element real-time B-scanner (fig. 27) and initially introduced by N. Bom from

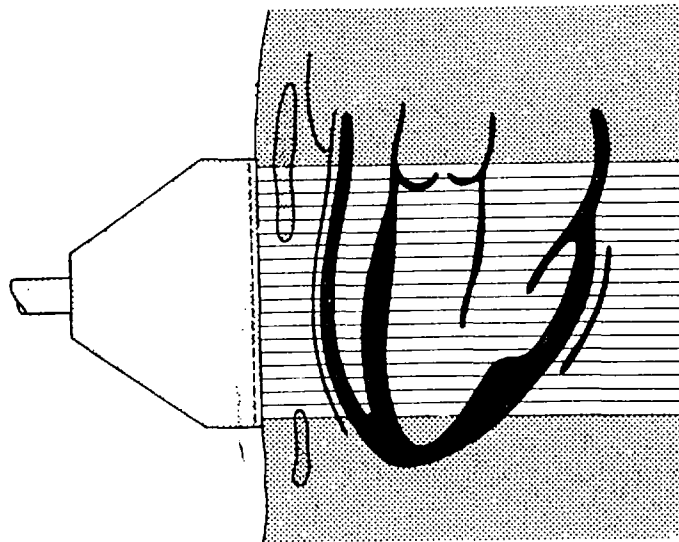


Figure 27. Diagrammatical representation of the multi-element system and anatomical orientation. (Courtesy of N. Bom, Rotterdam, The Netherlands).

Rotterdam.³¹ The system consists of an array of fixed elements which are rapidly excited in groups by means of electronic switching. The elements transmit short acoustic pulses into the tissue, and the returning echoes are displayed along the horizontal axis on the oscilloscope, while the vertical position of each line corresponds to the position of the respective elements. The number of transducer elements (20 elements with a length of 1cm and a width of 0.4cm) were chosen as a compromise for an optimal resolution near the left ventricle and posterior wall of the heart and the line

density on the display. Increasing the number of elements would decrease the single element width and thereby degrade the lateral resolution. The overall transducer size is 8 cm in length and 1 cm in width , which makes it easily manageable by hand. A particular disadvantage of this size is that in adults only part of the heart can be envisaged in real-time, and the transducer has to be moved in order to see other parts of the heart (fig. 28). However, a particu-

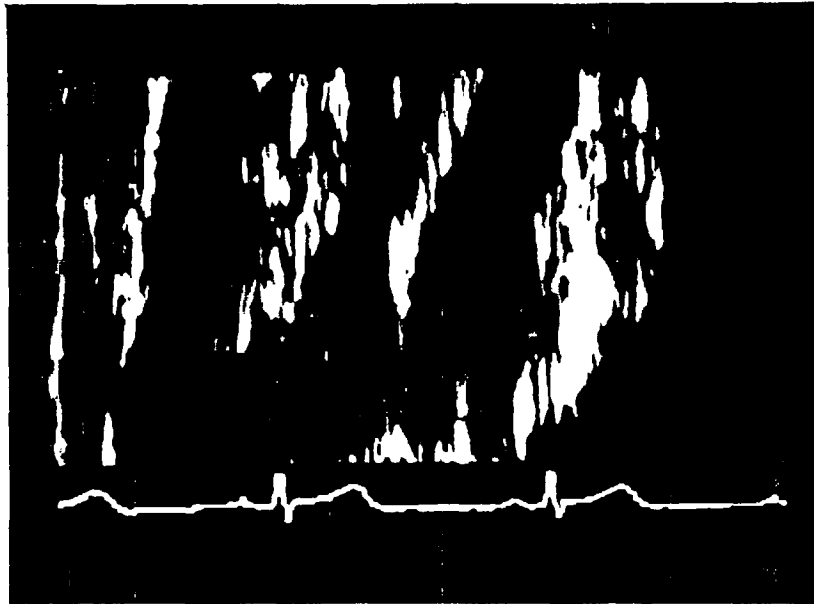


Figure 28. An updated scan as obtained from the multi-element system. (By courtesy of N. Bom, Rotterdam, the Netherlands).

lar advantage of this system is that the signal from any selected single element of the multi-scan transducer can be recorded in M-mode. The resolution of the early pictures at greater depths, however, was often not good enough for special M-scans or for reproduction in publications, but it is very important for the understanding of M-scanning features by comparing them with those of the two-dimensional display simultaneously. For better quality M-scan tracing one therefore often has to change to a larger separate single element

transducer. Later developments, however, have brought considerable improvement to overcome this difficulty. The clinical usefulness of this system has been shown in several publications^{32,33,34}. I had the opportunity to judge the prototype of the multiscan when it was evaluated for a multi-centre study by Dr. Pridie, who was working partly at Hammersmith Hospital and at Harefield Hospital.¹⁷ Later I had the opportunity to work with the multi-element system from ADR, which was given to me by courtesy of the Ministry of Health for evaluating the machine in diagnostic cardiology.

2. Electroscan or phased array

The latest development in multi-element system is the phased array ultrasound system, as initially introduced by Somers³⁵, and recently by Thurstone and Kisslo in cardiology with the electroscan.³⁶ This technique is represented diagrammatically in fig. 29. The initial system consisted of

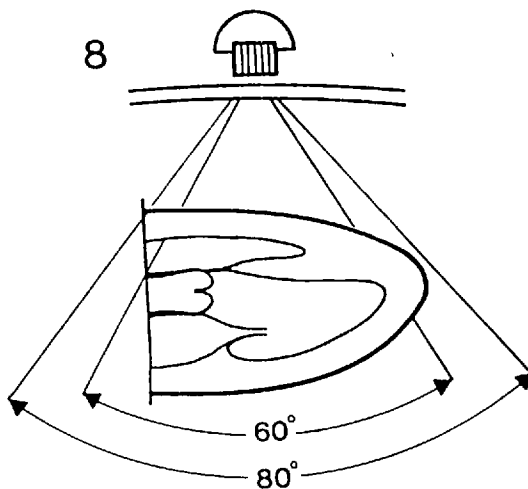


Figure 29. Diagrammatical representation of an electroscan, consisting of multiple small transducer elements which are excited in sequence to produce an electronically steered sector scan of 60° to 80°.

a linear array of 16 transducers, measuring only 14 x 24 mm at the side of skin contact. If all 16 transducers are pulsed at the same moment, the resulting ultrasound beam emerges in a direction perpendicular to the array of transducers. If they are pulsed in sequence, however, the wave front is propagated at an angle with respect to this perpendicular. Therefore, the principle of this system is to excite the 16 elements in rapidly changing time sequence, thus achieving

a rapidly changing angle of pulse propagation. In addition, electronic focusing can be produced by altering the pulsing sequence. The resulting images are displayed as circular sector frames, and the maximum field of view was initially a 60° sector with a 17 cm range (fig. 30). At this maximum

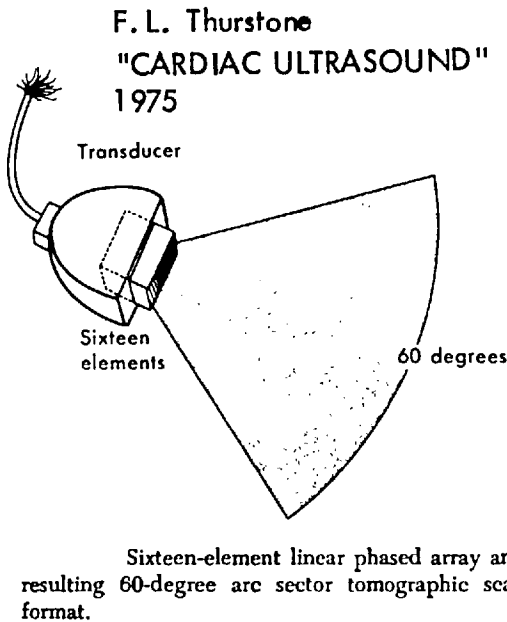


Figure 30. Diagrammatical illustration of a phased array sector scanner, (From Thurstone et al. in Gramiak, R. and Waag: Cardiac Ultrasound, The C.V. Mosby Co., St. Louis, 1975, p. 240).

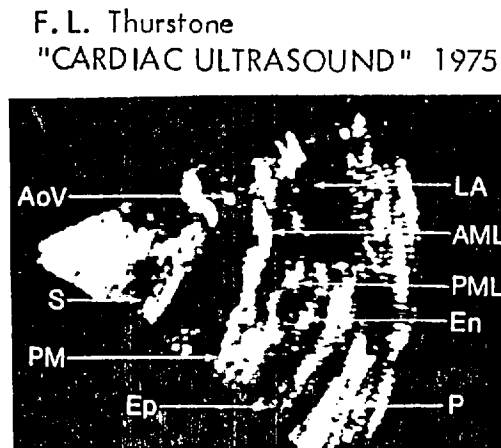


FIG. 16-4. Long axis of left ventricle. AoV, aortic valve cusps; Ep, epicardium; P, pericardium; En, endocardium.

Figure 31. A still frame obtained with a phased array sector scanner. (see reference above, p. 242).

range image frames consisting of 256 lines are generated at a rate of 20 frames per second. The layout of this system involves a digital computer as a programmable controller, which considerably adds to the cost of the equipment. The first reports of the clinical usefulness of this machine appeared recently.^{37,38} An example of a still frame from a recording with this system is shown in fig. 31. Transducers with wider angle phased arrays have recently been introduced but they still visualise only part of the heart in adults, and fail to define the near zone. This is a particular disadvantage in patients with huge dilatation of the cardiac chambers or hypertrophy of the ventricular walls, where, even with the apical view, a complete visualisation of the heart may be difficult. A recent example of a scan with a 79° phased array sector scanner, which was

obtained with the Toshiba SSH-10A, will be shown later
on p. 65.

CHAPTER V

ANATOMICAL ORIENTATION IN ECHOCARDIOGRAPHY

INTRODUCTION

The use of different ultrasound techniques and equipment makes it necessary to find generally accepted, standard cross-sectional planes for scanning cardiac patients. If such an agreement can be reached, independant observers will be able to follow up patients and to judge and use information previously obtained elsewhere.

This chapter is an attempt to find a solution to this most difficult problem in echocardiography. Real-time B-scanning (RTBS) is used as the reference for any ultrasound technique, whether one- or two-dimensional. It was chosen for three major reasons:

1. The scanning plane is fixed along the longitudinal axis of the applicator, as a physical property of the system used.

2. The direction of this plane can easily be judged during the scanning procedure, and fixed externally on a scale showing the angle of incidence, as on the particular equipment used (see fig. 32).

3. The visualisation of the different scanning planes needed for demonstration is achieved most easily by this technique.

It is impossible to separate the scanning technique of RTBS from the orientation and the description of the different cross-sectional planes, which necessitates a joint discussion in the

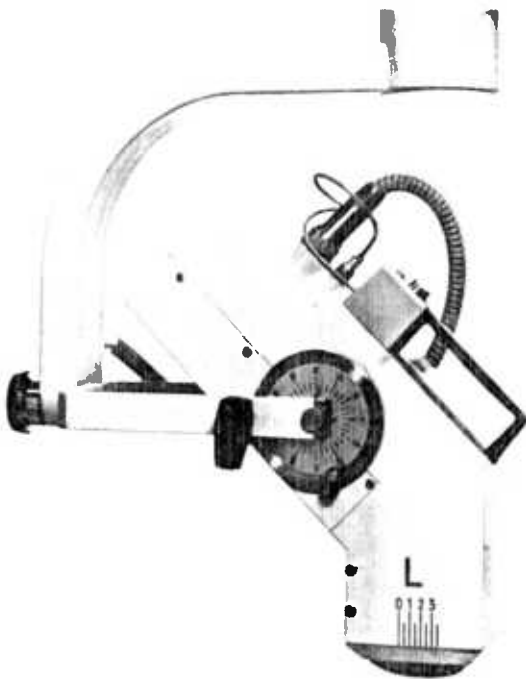


Figure 32. Applicator of the 'Vidoson', a mechanical real-time B-scanner, with an indicator to measure the exact angle of incidence of the cross-sectional scanning plane. (By permission of Siemens, Erlangen, Germany).

following chapters.

A. EXAMINATION TECHNIQUE IN REAL-TIME B-SCANNING

It seems of advantage to explain the real-time B-scanning technique at this point to facilitate the understanding of the different cross-sectional planes.

One palpates the apex beat (which may be marked on the chestwall), positions the right side of the applicator (see R on applicator in fig. 33 over this area, and directs the left side of the applicator towards the left mid-clavicular line. Thus one would cross-section through the heart as



Figure 33. Real-time B-scanning applicator along the longitudinal axis of the heart and in the LAO position so as to produce a cross-section equivalent to the angiographic RAO.

indicated on plane B in fig. 34. The exact plane would be found by ensuring that all internal landmarks (both anterior and posterior aortic roots with aorto-septal and aorto-mitral transition zones, both mitral valve leaflets, the inter-ventricular septum and the cardiac apex) are seen simultaneously on the television screen. This is a matter of trial and error, and it is of particular advantage in the system described here that the final angle of incidence can be fixed by the

bilateral suspension of the applicator. As seen earlier in fig. 32, p. 50, this can be achieved in a very simple and accurate manner. An angle of 45° is often too steep, and experience has shown that an angle of 30° in the LAO position is satisfactory in most patients. Thus the operator has only to ensure that the pre-set applicator is positioned in

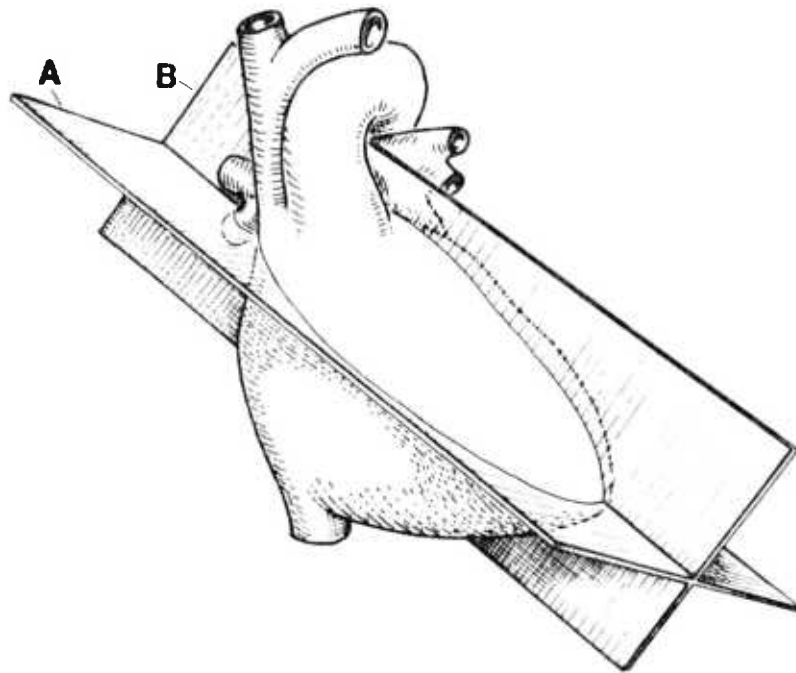


Figure 34. Diagrammatical representation of two perpendicular cross-sectional planes which correspond to the LAO (A) and RAO (B) projectional planes of angio-cardiography. For further detail see text.

such a way that the cross-sectional plane goes through all landmarks described earlier. An example of a real-time B-scan in this position is shown in fig. 35. The most easily

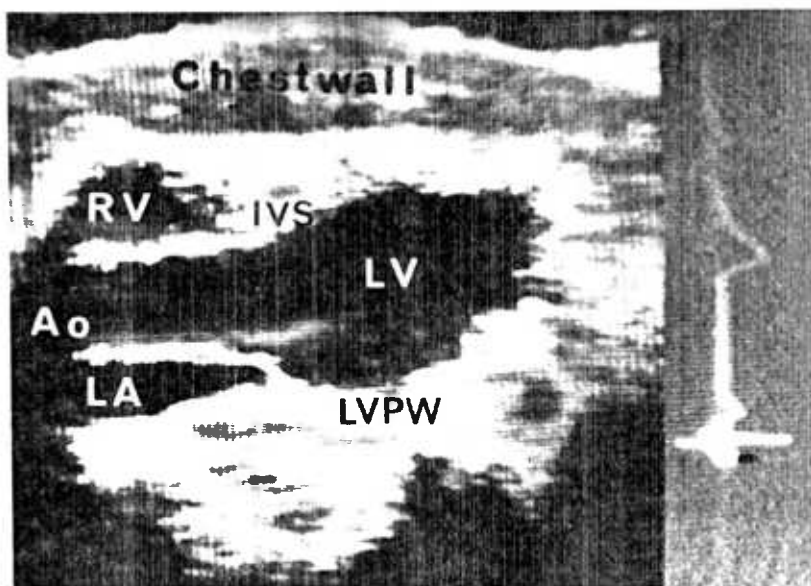


Figure 35. Linear real-time B-scan of a normal heart in early systole, as may be seen from the ECG and the previous end-diastolic after-glow of the open anterior mitral leaflet. This scan is taken in the 30° LAO applicator position and is referred to as the standard long axis scan in all our examinations.

visualised structures are the parallel moving aortic walls in continuity with the interventricular septum anteriorly and with the closed anterior mitral valve leaflet posteriorly. The afterglow on the cathode ray tube shows the previous open position of the anterior mitral leaflet during the phase of atrial systole. The myocardium is well delineated from the anterior chestwall and the right ventricular outflow tract is only just cross-sectioned at its most anterior level.

B. COMPARISON OF ANGIO- AND ECHOCARDIOGRAPHIC PLANES

It is particularly difficult for the novice to appreciate cardiac anatomy and pathology from the one-dimensional echogram because these are largely learned from photographs or diagrams of specimens, less often from the specimens themselves. The best established technique and the final arbiter for pre-operative investigation of the heart is angiography, and cardiologists have learned to appreciate the patients' changed structural relationships and their diagnoses by combining their three-dimensional knowledge from anatomy and pathology with the two-dimensional anatomical and functional information gained from the angiocardigram. This has recently been supported by studies using casts of human hearts to illustrate the cardiac anatomy and certain pathological abnormalities compared to angiograms.^{39,40}

Experience with combined M- and B-scan echocardiography for nearly seven years has helped us to bridge the gap between the one-dimensional presentation of relative anatomical structure in M-scanning and the true relationships, as seen two-dimensionally in RTBS and angiography, and three-dimensionally in post-mortem anatomy. Newer diagnostic techniques, however, have to be assessed by comparing their results with those of already established ones, and they are more easily understood when they resemble familiar images as closely as possible.

The representation of the heart during angiocardiology is a projection of the largest circumference of a contrast medium filled chamber, and lies perpendicular to the direction of the X-ray beam (see fig. 36). The three-dimensional cavity is reduced to a two-dimensional outline or area within which structural changes cannot be determined in relation to the depth of their real position. Two-dimensional echocardiography, however, produces a true cross-section through the heart, and the scanning plane lies therefore in line with the direction of the ultrasonic beam. Thus the projectional plane of angiocardiology and the corresponding echocardiographic cross-sectional plane are perpendicular to each other, as illustrated diagrammatically in fig. 36.

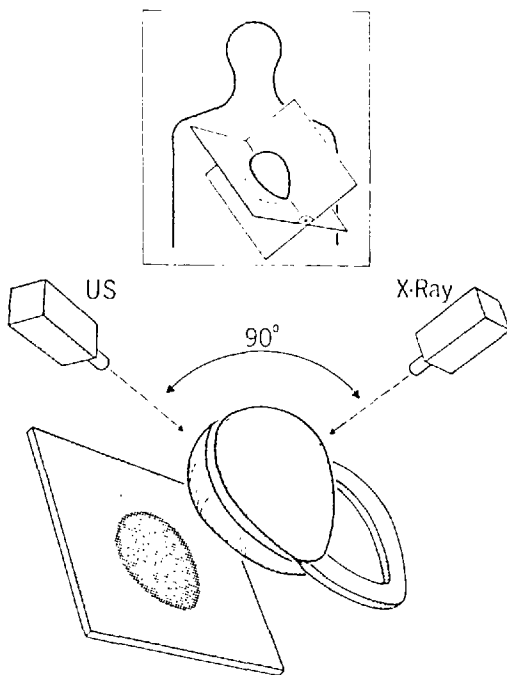


Figure 36. Diagrammatical orientation of beam directions from X-ray and ultrasound equipment and their corresponding images. In order to observe the same plane with both techniques, the applicators have to be positioned at an angle of 90° to each other. The X-ray applicator is tilted perpendicularly to the long axis of the heart to produce an exact projection in this axis. (see also cranio-caudal tilt later). B-scan ultrasound produces a true cross-section of the same plane in the direction of the ultrasonic waves. Therefore the ultrasound scanner has to be applied at right angles to the X-ray applicator.

The upper part of this diagram shows the position of the heart in the thorax and the two perpendicular planes indicating the left anterior-oblique (LAO) and the right anterior-oblique (RAO) planes of angiocardiology. The lower part of the diagram shows a comparable heart model which is hollow.

The X-ray applicator is in the LAO position and the resulting inner and outer contours of the model are projected onto the X-ray film plate, which is in the RAO plane. Thus the X-ray beam direction and the corresponding projectional plane are perpendicular. To achieve a true cross-sectional plane corresponding to the indicated projectional RAO plane, the ultrasound applicator has to be positioned in line with the RAO plane. The resulting cross-sectional plane is indicated by the dislocated slice which is cut out of the model, and is identical to the configuration of the projected image. Thus in order to image corresponding planes through the heart, the X-ray and ultrasound applicators have to be positioned at right angles to each other. Since the X-ray applicator is in addition often adjusted parallel to the body long-axis of the patient, a certain foreshortening is unavoidable in comparison with the true cross-sectional image of B-scan echocardiography. Consequently echocardiographically calculated volumes should overestimate angiographic volume determinations.

1. Standard long axis real-time B-scanning in RAO-angiographic projection

Fig. 37 facilitates the orientation for the examiner regarding the application of the transducer in relation to

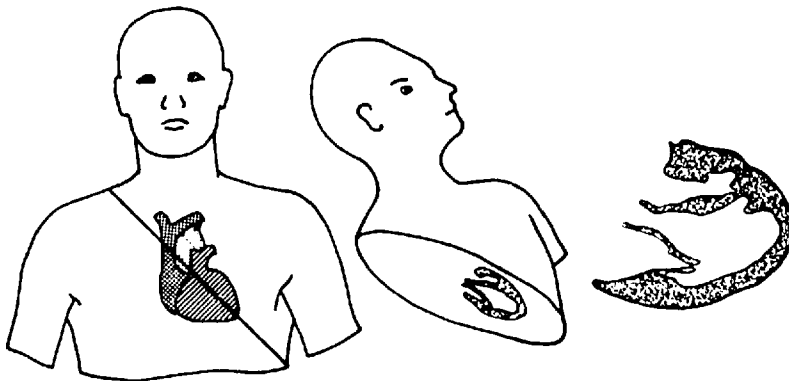


Figure 37. Diagrammatic orientation along the long axis of the heart, the corresponding cross-sectional plane as seen by the examiner, and the anatomical details of the long axis cross-sectional scan. For labelling of these structures see fig. 36.

the position of the heart in the B-scans presented in this thesis. The scanning plane is represented on the chestwall by a line roughly from the right shoulder to the left lower lateral thorax aperture. The single or multiple transducers are positioned above the heart, as indicated in fig. 38.

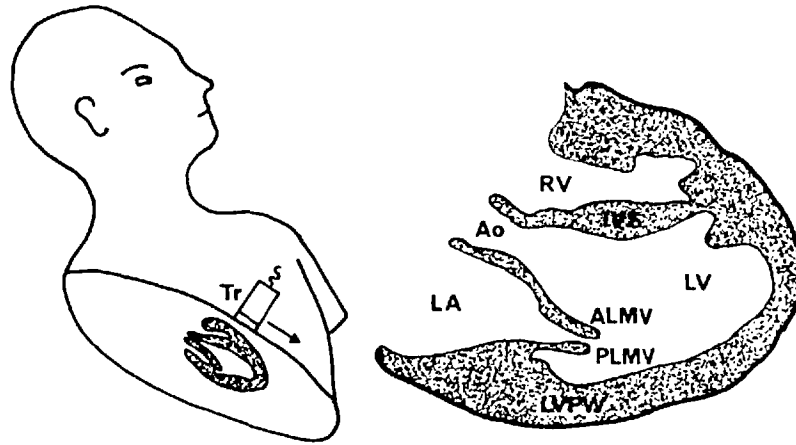


Figure 38. Diagrammatical orientation of the cardiac structures as seen in a long axis B-scan. (RV=right ventricle, Ao=aortic root, LV=left ventricle, IVS=interventricular septum, LA=left atrium, ALMV+PLMV=anterior and posterior mitral valve leaflets, LVPW=left ventricular posterior wall).

Comparing this figure with a real-time B-scan, as in fig. 35, makes it clear that the applicator is always placed above the structure indicated 'chestwall', pointing downwards, so that all distal structures seen from the probe appear below and all proximal structures above on the scans. Hence the upper side of the picture represents ventral, the lower part dorsal, the right side apical, and the left side basal parts of the heart. The ultrasound beam travels first through the chestwall, the right ventricular anterior wall, and then through the outflow tract of the right ventricle (RV), which may often be missed so that the anterior heart wall and interventricular septum (IVS) are not differentiated. Then the ultrasound pulse travels through the left ventricular posterior wall (LVPW). The aorta (Ao) is easily recognisable by the parallel movements of its walls. In normal anatomical relationships the anterior aortic root is conti-

nuous with the interventricular septum, and the posterior aortic root with the anterior leaflet of the mitral valve (ALMV). The area below the posterior aortic root limited by the mitral leaflets represents the left atrium (LA), and beyond the anterior aortic root and interventricular septum the right ventricle which is only just shown. The right ventricular cavity may be better displayed with right ventricular enlargement and with clockwise rotation of the heart, and is less well seen with anti-clockwise rotation in left ventricular hypertrophy and/or dilatation.

The display of the cardiac apex to the right or left side of the scans can easily be changed by a switch on some of the ultrasound equipment or by rotating the transducer or applicator through 180° on other. It appears of advantage to universally agree upon a fixed display mode with the apex to the right of the scans, since this would correspond to the orientation of the examiner, most often sitting on the right side of the patient. This would be of particular importance when carrying out conventional or triggered B-scanning, where a single probe is angulated, as seen in fig. 39.



The apex was imaged when the probe was directed to the right, and the base was shown when pointed cephalad or to the left (compare also fig. 37 on p. 55). Using such a standard display of cardiac B-scans would facilitate the comparison of examinations carried out by different observers.

Figure 39. A typical conventional and triggered B-scanning situation with the examiner on the right side of the patient. Pointing the probe downwards and to the right results in scanning the cardiac apex which is displayed to the right on the storage screen, thus facilitating the orientation.

If one wants to image the heart with real-time B-scanning in the longitudinal cross-section which resembles the angiocardigraphic projection of the patient in the right anterior oblique (RAO) position in relation to the X-ray camera, one has to place the echo applicator in an LAO position, as shown earlier in fig. 33 and explained on p. 51.

2. Standard long axis real-time B-scanning in LAO- angio projection

For this cross-sectional plane the real-time B-scanning applicator has to be positioned in the RAO position, as illustrated in fig. 40. This would correspond to the plane

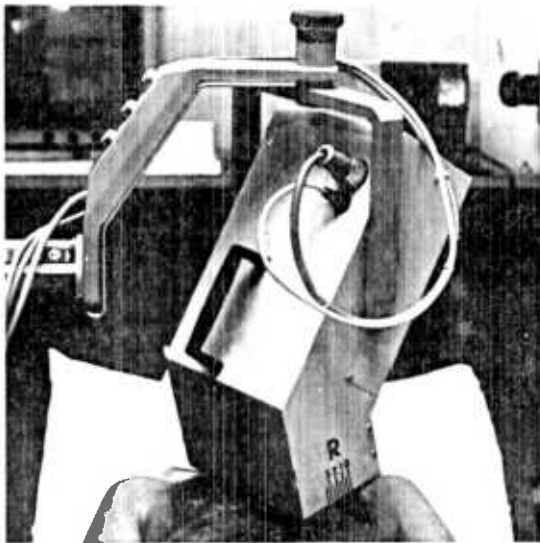


Figure 40. RAO ultrasonic applicator position on a prone patient, to image the equivalent of the LAO projection plane of angiocardiology.

A of fig. 34, p. 52. The easiest way to accomplish this is to change from LAO to RAO position of the applicator under visual guidance, and fix the angle of incidence in the new position at 30° . Thus the anatomical orientation changes slightly, but all landmarks are still visible. An example of a real-time B-scan in this plane is shown in fig. 41. The shape of the left ventricle changes from an ellipsoidal to a slightly more spherical one, and since the beam is directed from a slightly more ante-

rior angle in relation to the heart, only a little more of the right ventricular outflow tract is visualised in normals. The increase in right ventricular diameter is even more pronounced when the patient is additionally rotated into a left lateral position. This already indicates the implication

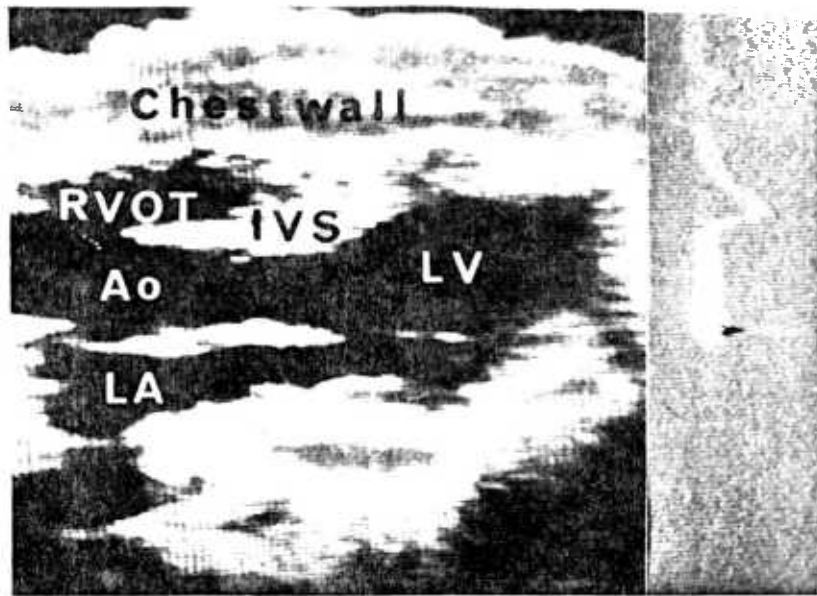


Figure 41. Real-time B-scan of a normal individual taken in the longitudinal LAO applicator position. For orientation see fig. 35.

of patient and transducer position for consistent determination, particularly of right ventricular internal diameters in patients with right ventricular volume overload.

3. Long axis real-time B-scanning in anteroposterior (a-p) angio projection

An absolute equivalent to this X-ray position cannot be obtained with a standard real-time B-scanning application on the chestwall, since the applicator will have to be positioned laterally in the mid-axillary line, where lung tissue is positioned between chestwall and heart. The alveolar air would produce a nearly complete reflection of the ultrasonic beam, because of the large acoustic impedance difference between tissue and air. However, placing the transducer over the cardiac apex and pointing it towards the base, so that the heart is imaged in its longitudinal axis in a plane which is as frontal as possible, a cross-section of the heart may be obtained resembling the a-p X-ray projection, but without the foreshortening seen in the latter technique (see later 'Apical long axis real-time B-scanning, p. 64').

4. Real-time B-scanning in left or right lateral angio-projection

An equivalent to this angio-position is best achieved in real-time B-scanning with the applicator in an approximately vertical a-p position parallel to the left sternal border, as illustrated in fig. 42. This cross-section would



Figure 42. Real-time B-scan applicator position in anteroposterior direction, which produces a cross-section comparable to the right or left lateral angiographic plane.

scan in an oblique plane through the heart, which again would result in a more spherical left ventricular shape. An example of a real-time B-scan in this plane is shown in fig. 43. The anatomical orientation is roughly maintained, but one of the landmarks, the cardiac apex, is missing. This plane is rarely of additional value and only used in patients with a small cardiac window or with difficult acoustic properties for initial anatomical orientation.

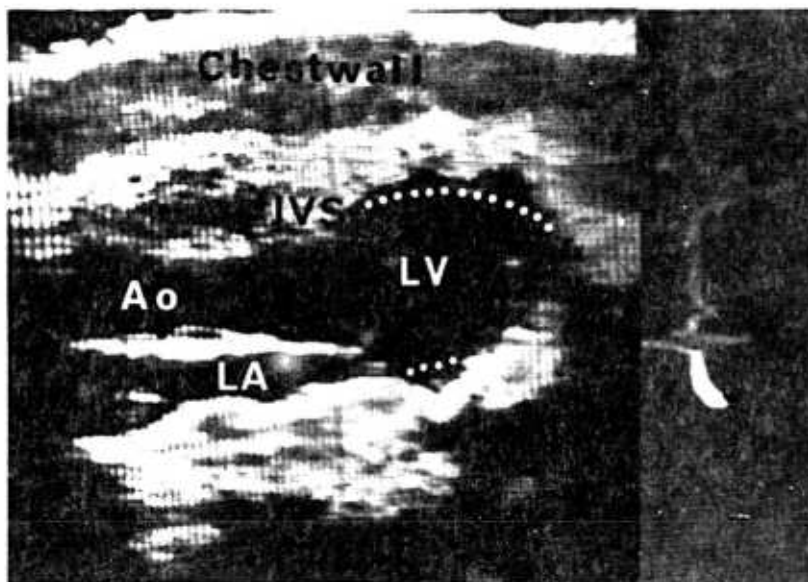


Figure 43. Real-time B-scan in the vertical applicator position of fig. 38. The slight irregularities in the left ventricular walls are produced by overlying ribs. For orientation see fig. 35.

5. Standard long axis in cranio-caudal tilt RAO
angiographic projection

In this angiographic position with the X-ray camera in a correspondingly modified right anterior-oblique position, a true longitudinal outline of the left ventricle will be obtained. The necessity for such a cranio-caudal tilt is that the heart has undergone essentially three major displacements during the embryological development, diagrammatically indicated in fig. 14.

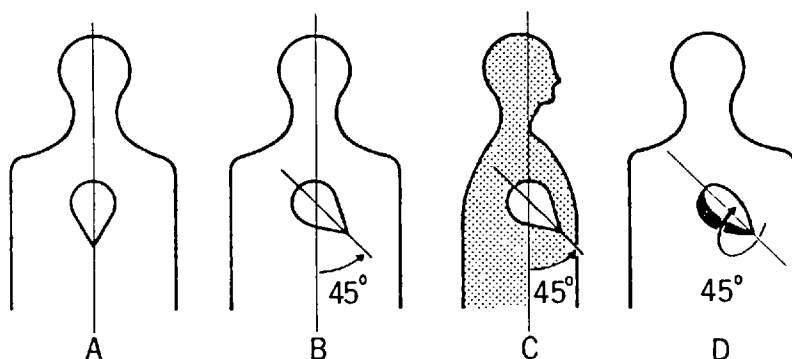


Figure 44. Diagrammatical illustration of the three major embryological heart displacements from the vertical position to the left, anteriorly, and with clockwise rotation.

The displacements are always approximately 45° from the vertical (A), to the left (B) and anteriorly (C), and also in the form of a rotation around the longitudinal axis of the heart (D). If the position (C) is therefore radiographically viewed from the conventional RAO-position, a certain foreshortening must result (see fig. 34), and only if the cranio-caudal tilt images perpendicularly to the longitudinal axis of the heart will a true longitudinal projection result (see also fig. 45 and compare with fig. 36). The area thus obtained, which is in the LAO applicator position, closely resembles the true cross-sectional area of real-time B-scanning of the same plane. Since the conventional RAO angiographic projection is more widely used than the cranio-caudal tilt,

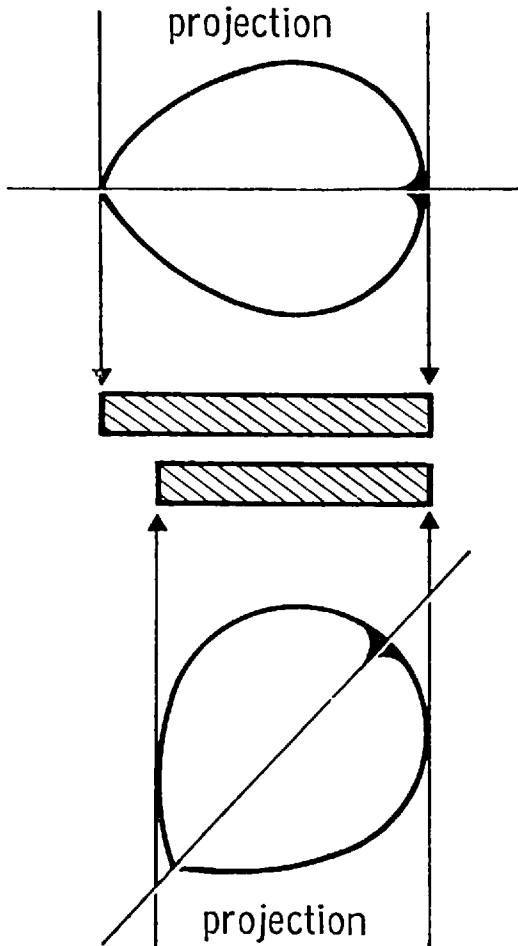


Figure 45. Diagrammatical representation of the projectional X-ray plane of the heart. A true long axis plane is achieved only when the X-ray beams are perpendicular to the long axis of the heart. A foreshortening occurs with an oblique scanning position in the usual RAO or LAO planes.

all our present comparisons rely on correlations with this angio presentation. One can perhaps assume that only a negligible difference in left ventricular area may result when comparing both angio-projectional planes with each other, although no large scale comparison has yet been undertaken. Nevertheless, volume calculations from angiograms obtained with this cranio-

causal tilt should correlate best with those measured from real-time cross-sectional echograms.

6. Standard short axis or transverse real-time B-scanning (LAO transducer position)

For this real-time B-scanning plane no X-ray projectional plane is available since the X-ray camera would have to be positioned in a direction from base to apex or vice versa. Fig. 46 illustrates how the applicator is positioned on the chestwall roughly in a line from the left shoulder to the right lower lateral thorax wall and in the LAO transducer position, thus being in a perpendicular plane to the standard longitudinal or cross-sectional plane in RAO angio-projection, as previously described.

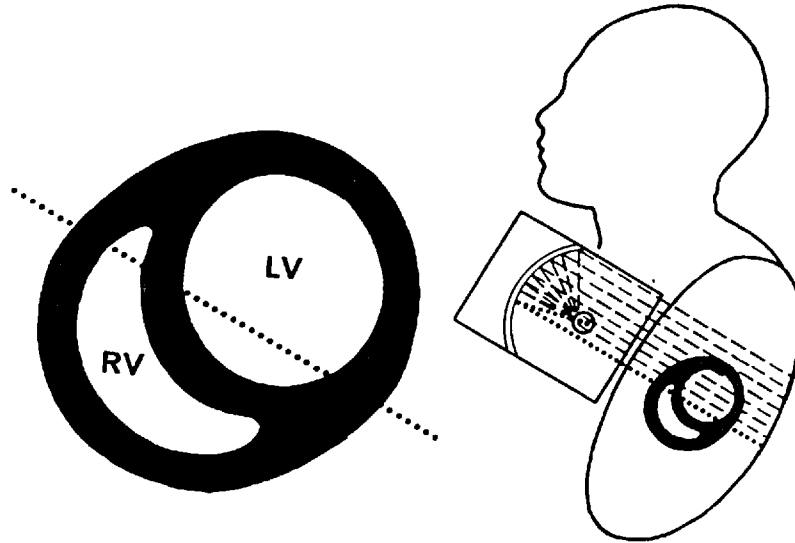


Figure 46. Diagrammatical illustration of orientation in transverse real-time B-scan applicator position and the corresponding scan. For further explanations see text.

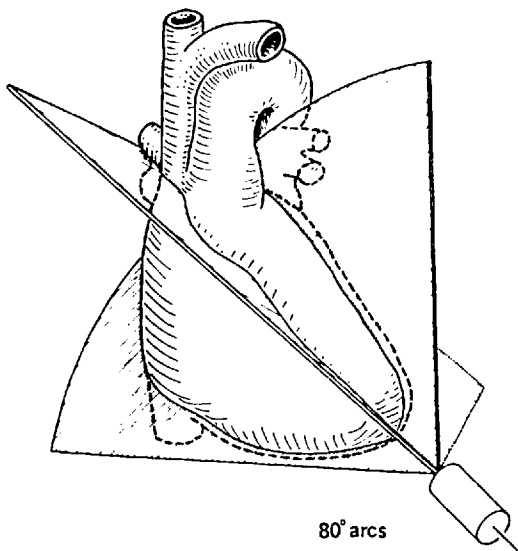
Observing this plane from below explains the rounded left ventricular (LV) cavity on the right of our scans, and the half-moon-shaped right ventricle (RV) on the left (see also fig. 106 , p. 133). The dotted line in the diagram indicates the normal pathway of the standard single ultrasonic beam and shows the restricted visualisation of the right ventricular outflow tract in M-scanning.

The oblique position of the heart with regard to the anterior chestwall (see C in fig. 44) makes it necessary to tilt the applicator up to 45° towards the right shoulder to form a right angle between the direction of the soundwaves and the long axis of the heart. Thus an oblique short axis cross-sectional plane can be avoided. In this way transverse real-time B-scanning may be performed at different levels of the heart, depending on whether the interatrial septum, the aorta, the atrio-ventricular valve rings or orifices, the chordal or the papillary muscle regions near the apex are to be visualised.

7. Apical long axis real-time B-scanning in any desired plane

Placing the transducer over the apex and pointing it towards the cardiac base theoretically produces longitudinal cross-sections in any desired plane, including the earlier described ones resembling the LAO, RAO, a-p, and lateral projectional planes of angiocardiology. The rotation of the scanning plane through 360° around an axis such as the apex is theoretically again most easily achieved with a sector scanner, and the best view, showing the entire heart, is obviously best obtained with a wide angle sector-scanner. In practice, however, only few angles are satisfactory at the present stage of lateral resolution of available sector-scanners. This technique has been called 'Four chamber view', which may be misleading. Four chambers can be visualised from many different positions on the chestwall. We prefer to call this particular view 'apical long axis view', which can resemble any desired projectional plane of angiocardiology, depending on the rotation of the probe. The particular advantage of this view is that the apex and the base are better simultaneously visualised, as they are rarely seen within one frame when examining adults with sector-scanners from the standard position on the chestwall.

The appropriate applicator position is shown diagramma-



tically in fig. 47, and rotation of the probe produces the two cross-sectional planes equivalent to the RAO and LAO angiographic projections. A long axis apical view obtained with the Toshiba

Figure 47. Diagrammatic illustration of the apical long axis view with a real-time sector scanner in the equivalent of the RAO and LAO angiographic projectional planes.

79° phased-array sector scanner is shown in fig. 48.

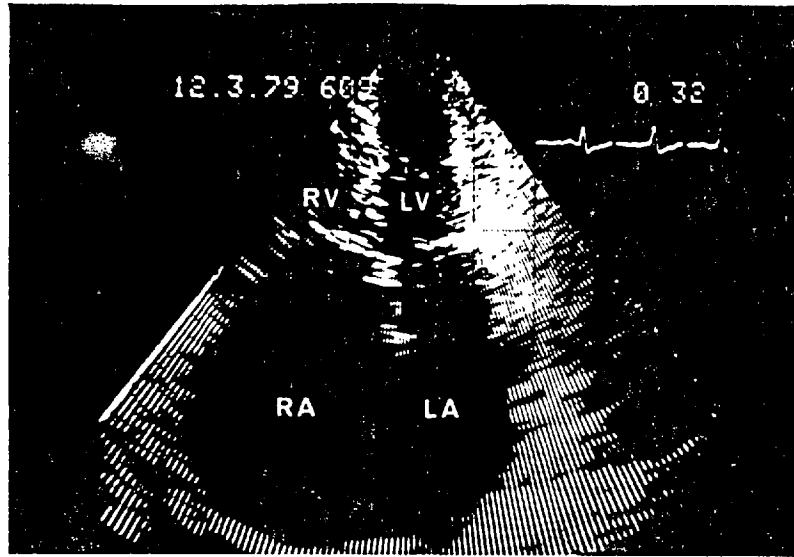


Figure 48. Apical long axis real-time B-scan of a patient with an atrial septal defect, showing a huge right atrial enlargement and a communication between the atria. (RA, LA=right and left atrium, RV, LV=right and left ventricle).

Apex and base of the heart are sometimes ill-defined by linear scanners as well, although the entire heart may lie within the cross-sectional plane. This is due to the unfavorable angle between apex and transducer direction from the standard position.

CHAPTER VI

APPLICATION OF
UNMODIFIED AND MODIFIED CONVENTIONAL B-SCANNING
IN CLINICAL CARDIOLOGY

A. CONVENTIONAL B-SCANNING (CBS) TECHNIQUE

Many hospitals use commercial B-scan equipment routinely, mainly in their obstetrics and gastroenterology departments. With good inter-departmental relations it would be quite easy and initially inexpensive for colleagues interested in cardiology to use this equipment as well to perform two-dimensional echocardiography and to make some comments on the structural and functional changes of the heart. It was therefore felt that this B-scan method, and particularly its derivative, the continuous sweep technique (next chapter, p. 71), should be described although they were found while developing the triggered B-scanning technique.

The application of conventional B-scanning techniques to static structures is in principle quite simple. Fig. 49 shows a typical obstetrical scan where the position of a



Figure 49. Conventional B-scan of a fetus, obtained prior to fetal heart recordings with M-scan echocardiography. The arrow indicates the position of the heart. (PL=placenta, L=limb, H=head).

fetus prior to the echographic investigation of the fetal heart has been determined. Scanning the object from different angles increases the echographic information. Using the

same technique on a constantly moving structure such as the heart, one cannot avoid a certain blurring of the scan. A conventional B-scan of an adult heart has been shown in fig. 14, p. 34, at a scale of 1:2 (1 cm on the grid representing 2 cm in tissue).

1. Scanning procedure

For constant results it is necessary to fix the scanning plane in a reproduceable fashion through the heart. This has to be done in both techniques, conventional and triggered B-scanning, in a similar way as earlier described for real-time B-scanning. We felt it necessary to extend the method which King⁴¹ used for volume determinations with triggered B-scanning (see p. 79). His two landmarks, one of which is fixed with ultrasound internally at the aortic root, and the other, the apex, is fixed externally by palpation, are supplemented by three additional landmarks:

- Landmark 1: the aortic root which is easily recognizable in A- and B-mode by the parallel movements of its walls. According to the size of the heart, the probe is placed in the third or fifth intercostal space in the mid-clavicular line and is pointed towards the right shoulder of the supine patient.

- Landmark 2: aorto-mitral transition zone (AMTZ) which should always be observed continuously during the entire sweep from the posterior aortic root to the anterior leaflet of the mitral valve.

- Landmarks 3 and 4: the mitral leaflets. The anterior leaflet should always be observed continuously in A-mode during the entire sweep from the posterior aortic root to its characteristic M-shape movement on the slave scope. Ideally and particularly for volume determinations, the scanning planes must also go through the base of both anterior and posterior leaflets of the mitral valve in order to outline the left ventricular cavity at end-diastole.

- Landmark 5: the apex, which in most cases can be palpated and marked on the chestwall. In the absence of a palpable apex beat the position must be fixed by the A- and B- scan, and the corresponding position of the transducer marked in the particular plane, where all landmarks can be visualised.

Landmarks 1 and 5 are those described by King⁴¹. However, it seemed necessary to supplement these with landmarks 2, 3, and 4 since five points, even if they do not lie on a line, will fix a plane, whereas two points cannot do this. Experience has shown that the application of these five prescribed landmarks leads to a well-defined scanning plane through the heart with very little room for error if the transducer is always angled at 45° in an LAO application. This axis is therefore taken as standard long axis through the heart.

In the conventional B-scanning technique the transducer is placed preferably over landmark 3, and is moved to and fro with minimum possible gain to record all structures in the prescribed scanning plane. The constant overwriting of end-diastolic movements by end-systolic movements of the heart walls finally results in an echo free space which represents the end-diastolic cross-sectional area of the left ventricle (see fig. 14, p.34). This size may be an important statement when the heart appears to be enlarged on the chest X-ray film.

2. Results

A particular example of an aortic aneurism is shown in fig. 50. The aortic root is on the left and oddly distorted. The structure above the label (Ao) was initially thought to represent the posterior aortic root, and it was impossible to identify the structure below. Only after switching to the triggered B-scanning technique, which is explained later, a clarification was possible.

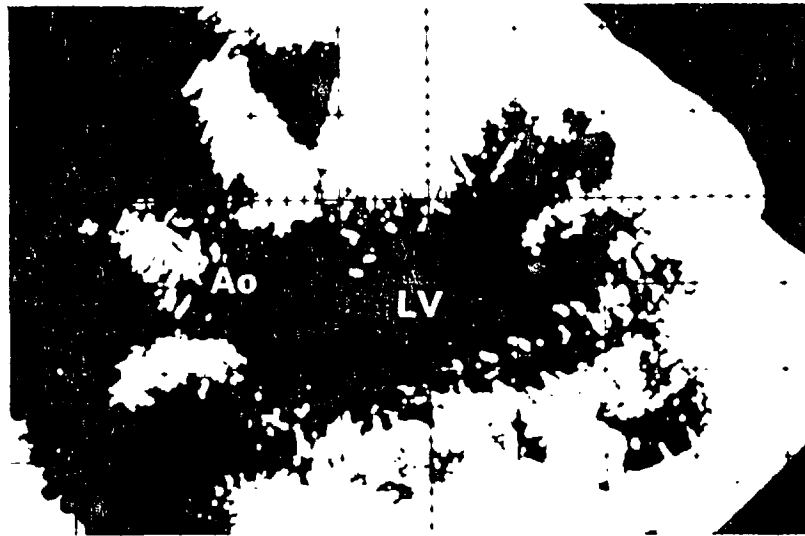


Figure 50. Conventional B-scan of a patient with an aortic aneurism. The blurring of the heart structures during the cardiac cycle made the diagnosis possible only after carrying out a triggered B-scan, as shown in fig. 51. (Ao=aortic root, LV=left ventricle).

This is shown in fig. 51, and made us realise that the lower structure represented the posteriorly diverging aortic wall of a huge aortic aneurism, and that the structure between the aortic walls represented the aortic valve cusps, which were recorded only when closing incompletely in diastole.

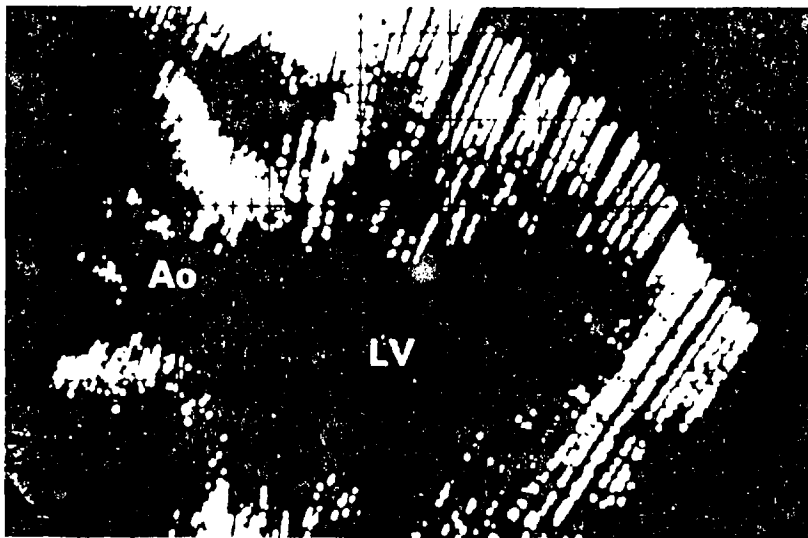


Figure 51. Triggered B-scan of the patient in fig. 50, now clearly showing the thickened aortic root and incompletely closed aortic cusps. (Ao=aortic root, LV=left ventricle).

3. Discussion

Fig. 52 illustrates how the continuous overwriting of end-systolic over end-diastolic wall motions (compare the aortic roots in fig. 50) creates a smaller virtual internal dimension (a) as compared to the real diameter (b).

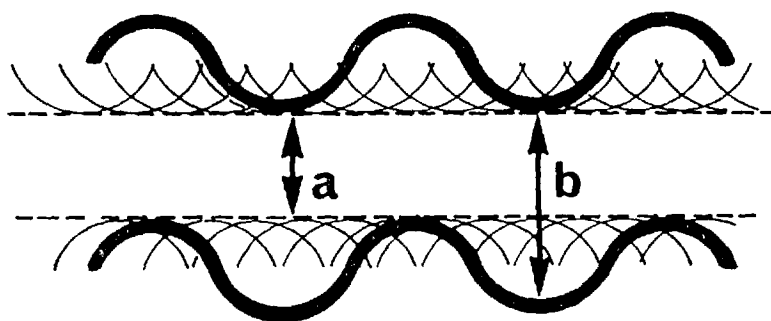


Figure 52. Diagrammatical illustration of continuous overwriting of aortic root motions with the conventional B-scanning technique, producing a virtual lumen (a) as compared to the real lumen (b) obtained with the continuous sweep technique (see text).

The same is true for measurements of the left ventricular cavity, and the difference between the virtual and real area will depend on the amplitude of the heart wall motion (compare fig. 14, p. 34). Thus there will always be an underestimation of cavity size with this method. It was therefore felt that this type of technique may not give enough information in relation to the time which has to be spent to obtain and interpret such a two-dimensional scan of the heart, and we therefore directed our interest more towards the following two techniques.

B. CONTINUOUS SWEEP TECHNIQUE (CST)

This method was also a by-product of our triggered B-scanning technique, and was used in order to find a faster way of defining the best long axis plane through the heart

for our volume studies. To repeat a triggered B-scan several times would have been too much time-consuming, therefore a rapid sweep was carried out until the plane seemed suitable for our purposes, with all the landmarks needed.

1. Scanning procedure

Once the scanning plane has been determined and fixed by the transducer gantry and by trial and error, so that strong echoes are obtained from all five landmarks, the transducer is placed in contact with the patient's skin over landmark 3 and turned in the direction of the right shoulder until the aortic root is displayed. Fig. 39, p.57 shows such a scanning situation with the Picker Echoview IV Laminograph, and also the fixed scanning plane as determined by the position of the gantry. Watching the storage scope (the simultaneous observation of the reflected heart structures in A-mode is possible on a parallel slave scope), the probe is swept through landmarks 2 to 4 towards the cardiac apex. The velocity of this sweep (between 10-30 cardiac cycles) is adjusted to the type of information desired from the scan. If the apex happens not to be displayed satisfactorily in this sweep, then the transducer must be placed, for example, around a rib in a new position of the same scanning plane, in order to bring up all structures. It is clear that many conditions have to be met in order to obtain a continuous sweep B-scan of a rapidly moving organ such as the heart. Even with a skilled echocardiographer a certain extent of blurring is inevitable and the results of the investigation depend to a large extent on the manual and on the technical skill and anatomical perceptiveness of the observer.

2. Results

A typical example of a CST-scan is shown in fig. 53,

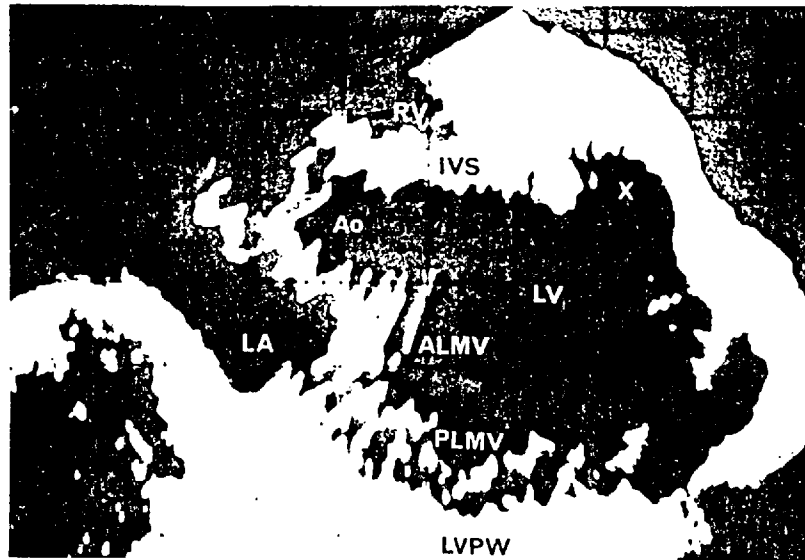


Figure 53. A continuous sweep B-scan of the heart illustrates the similarity of structure motion, as known from M-scanning (aortic root (Ao) and anterior leaflet of the mitral valve (ALMV)), with the simultaneous display of the true anatomical relationships within the left ventricle (LV). The area (x) is the typical artefact of a rib shadow. (LA=left atrium, RV=right ventricle, IVS=interventricular septum, PLMV=posterior leaflet of the mitral valve, LVPW=left ventricular posterior wall). For further information see text.

with normal intracardiac structure relationships. The continuous motion of the transducer avoids the blurring of the wall motion experienced with the conventional B-scanning technique, by recording changed positions of the heart at constantly changed positions on the storage oscilloscope. Thus this image is similar to a continuous sweep in M-scanning, however, the B-scanner records position and motions simultaneously, so that a true overall outline of the cardiac boundaries can be appreciated in addition to their motions in time. In this figure the parallel motion of the aortic walls can be seen, leading anteriorly into the interventricular septum, and posteriorly into the increasing amplitude of the anterior mitral valve leaflet towards its tip. The area (x) is a typical artefact produced by an overlying rib. The normal relationship of left atrial to

left ventricular cavity area and that of the right ventricular outflow tract can readily be appreciated, although the former two are equally slightly enlarged (1 square=2 cm in tissue).

A comparatively much larger heart is shown in fig. 54

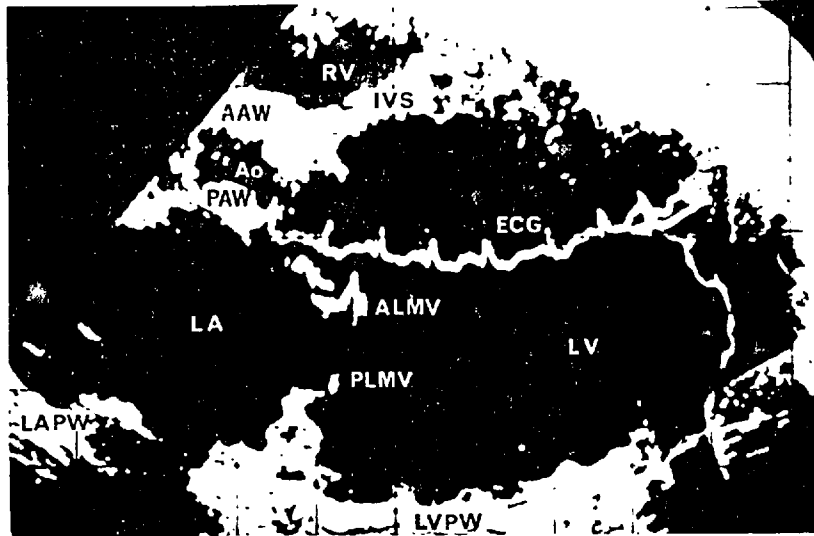


Figure 54. Heart scan with the continuous sweep technique of a patient with congestive cardiomyopathy. (A and PAW=anterior and posterior aortic wall, here blurred by an aortic valve prothesis). For further orientation see fig. 53.

with a changed left atrial to left ventricular size relationship . The left ventricle (LV) has a transverse diameter of about 10 cm, and the left atrium (LA) of about 7 cm. Here the posterior leaflet of the mitral valve (PLMV) is more clearly seen than in fig. 53, and the initial part of the M-shape of the anterior mitral valve leaflet (ALMV) can be appreciated. The interventricular septum (IVS) is of normal thickness (about 1 cm) and the added electrocardiogram (ECG) of the patient in sinus rhythm shows by the regular R-R intervals that the sweep was carried out with a continuous and rather regular sweeping motion. The flat amplitude of left ventricular posterior wall motion can readily be seen, a hallmark of congestive cardiomyopathy, which was finally diagnosed in this patient.

3. Discussion

With this method it was believed that a new, viable and simple B-scanning technique was found, which was called Continuous Sweep Technique (CST) in B-scanning, in order to differentiate it from the Continuous Sweep Technique in M-scanning. However, further search of the literature revealed that this technique of heart structure visualisation had already been described as a possibility five years earlier, and was called 'Ultrasono-tomo-kymography'.

I felt at the time and still feel that this method should be encouraged much more, especially if no real-time scanner is available, since valuable information could be extracted from such scans as compared to M-scans, and no more skill is required to obtain good CST-scans. Up to now this method has been nearly completely neglected in clinical cardiology, probably because of the earlier difficulties in understanding the examples given in the limited literature. I left this method because the compound B-scanner which we had by courtesy of Picker Co. Ltd for our volume studies went back in early 1974. Furthermore after the first experience in real-time B-scanning in the same year, this new method appeared already to have superseded the former conventional approach.

If one wanted to use the CST method for functional information, one could envisage left ventricular volume measurements with the area-length method to be obtained from a single CST-scan, as shown diagrammatically in fig. 55, using the newer, large storage scopes, available with compound B-scanners, and in conjunction for example with a hard-copier. Thus the heart can be imaged in full or double full size and the excursions of the wall movements are large enough to show their precise amplitudes, provided an even sweep from the aortic root to the apex in about 15-20 heartbeats is performed. By continuously connecting the points of maximum and minimum excursions of the inner left ventricular wall, end-systolic and end-diastolic areas may be delineated and volumes calculated

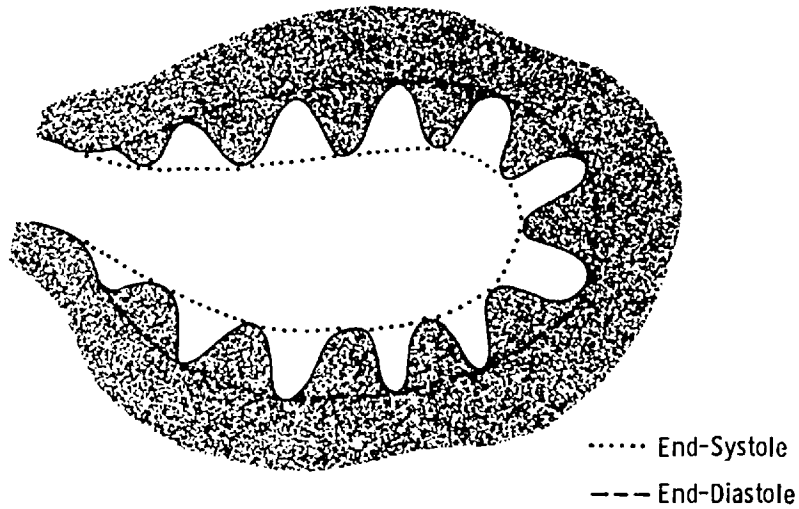


Figure 55. Diagrammatical representation of a continuous sweep B-scan to illustrate the possibility of delineating end-systolic and end-diastolic left ventricular areas for volume determinations. For further information see text.

by the area-length method of Dodge⁴³. The biggest disadvantage of this scanning method lies in the strong blurring of the wall motions when the sweep of the transducer cannot encompass the entire left ventricle from one position, but must be completed from another chest point in the same plane.

In conclusion, the continuous sweep technique in B-scanning is a valuable, non-invasive technique for two-dimensional visualisation of the heart and its motion, and should be particularly encouraged in those centres where real-time B-scanning is not yet available. Even functional data may be obtained from this method.

C. TRIGGERED B-SCAN ECHOCARDIOGRAPHY (TBS)

For quantitative measurements use is made of the periodicity of the heart motion and the B-scan equipment must be modified so that either the ultrasound pulses are emit-

ted and displayed for only 10 msec. during each cardiac cycle, or on continuous emission this storage scope is activated only for a short fraction of a second during each heart period. Thus each line describes only a small part of the scan, and the compounding of about 90 to 120 such lines enables the building up of a 'stop-action' or 'stop-motion' scan. Thus the ultrasonic method of imaging the heart does not differ from M-scanning in the type of information used, but in the way in which this echo information is processed and displayed. Both methods employ the B-mode information as discussed on p.26 .

'Stop-action' or 'stop-motion' imaging of the heart with a compound B-scanner is very different from that with a real-time B-scanner. The latter produces a frozen frame of a rapidly moving cross-section of the heart with all structures displayed almost simultaneously on a cathode ray tube and recorded on a video tape or film. We therefore prefer to speak of a 'stop-action' or 'stop-motion' frame or just of a single frame of a real-time B-scan at a certain phase of the cardiac cycle. Triggered B-scans are also static cross-sections of the heart in any given plane, and the electrocardiogram of the patient is also used as a synchronising and timing signal, however, in order to store successive B-mode information always at the same moment of the cardiac cycle, as initially worked out by King.⁴¹

Fig. 56 illustrates how the peak of the R-wave is used to trigger either the emission of ultrasonic pulses for 10 msec. or the recording on the storage scope for the same fraction of time during continuous emission, because the peak is most easily detected electronically. The continuous line of the electrocardiogram shows the corresponding phase of the cardiac cycle. In this diagrammatical example the emission is gated directly at the peak of the R-wave, thus a single B-mode line is recorded on the storage scope in the initial transducer position on the left side of the figure. For the remainder of the cardiac cycle no more echoes are recorded, and this time is used (central part of the fig.)

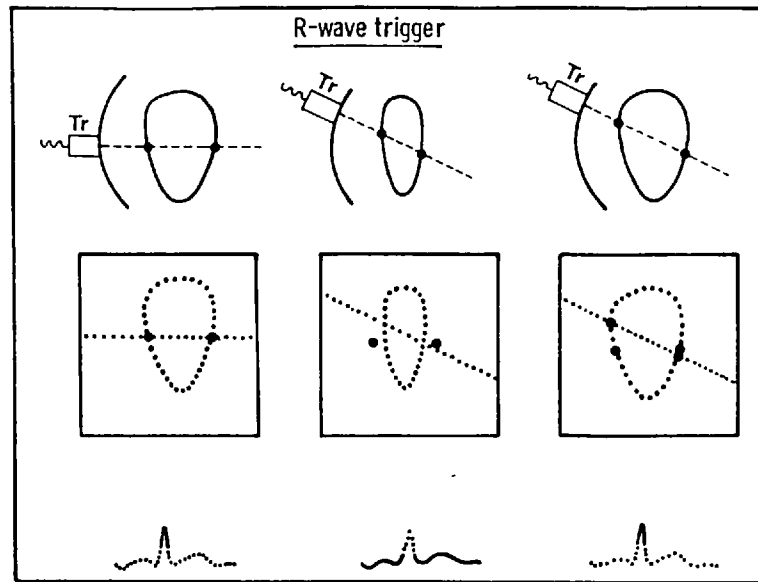


Figure 56. Diagrammatical illustration of an R-wave trigger facility. The simultaneous ECG display indicates that the trigger signal is obtained only at the R-wave peak display to store a B-mode signal. Thus only in positions 1 and 3 the different transducer (Tr) positions are recorded. For further information see text..

to move the transducer to another position of a pre-selected scanning plane. The corresponding B-mode line is only recorded when the next QRS-complex on the electrocardiogram is displayed and electronically registered, as seen on the right side of the figure. The image build-up is monitored during the entire process and requires up to two minutes. The variable delay control of the R-wave trigger allows any phase of the cardiac cycle to be chosen. Since I was mostly interested in functional parameters from the triggered B-scans for volume determinations, I used only end-systolic and end-diastolic trigger signals.

The scanning methods used will be described in the following chapter on the volume study by triggered B-scanning. The detection of any changes of cardiac structures with triggered B-scanning was thus a by-product of this study, and examples of the diagnostic value of this method will be given later on p. 101.

CHAPTER VII

TRIGGERED B-SCANNING

IN LEFT VENTRICULAR VOLUME DETERMINATION

A. INTRODUCTION

Many authors have used the cube of the left ventricular (LV) internal diameter of the M-scan echocardiogram to calculate LV volumes and to correlate these with the corresponding volumes obtained from the LV angiograms.⁴⁴⁻⁵⁰ A surprisingly good correlation was generally obtained for small ventricles, but this did not hold for dilated ones.⁴⁶⁻⁵⁰ Since many of the patients studied have dilated hearts an improvement in method appeared necessary. There was reluctance in departing from ultrasound techniques with their non-invasive character and safety, and I looked to an obvious extension of the one-dimensional M-scan measurement, namely to cross-sectional echocardiography by triggered B-scanning.¹² A pilot study by King⁴¹ on eight patients, however, also showed a rather poor correlation with the biplane angiographic data for larger volumes. It was felt that this method had shown its usefulness for assessing LV volumes and had many advantages over angiocardiology, and a further refinement of King's approach to this problem seemed worthwhile.

B. METHODS AND PATIENTS

To achieve the two-dimensional echograms the Picker Echoview IV Laminograph was used as earlier described on p. 19. The timing of the short ultrasound emission is shown as a time marker line on a displayed electrocardiogram as well as on a mitral valve echogram, obtained as a preliminary to the triggered B-scan (fig. 57). However, I found that neither the peak of the R-wave invariably marks end-diastole nor the end of the T-wave end-systole. Therefore fixing the emission burst by reference to the electrocardiogram alone is in my opinion unsatisfactory. Furthermore the T-wave is not always clearly defined. In all cases the mitral valve echogram is therefore utilised to fix the moments of end-systole and end-diastole. This figure shows

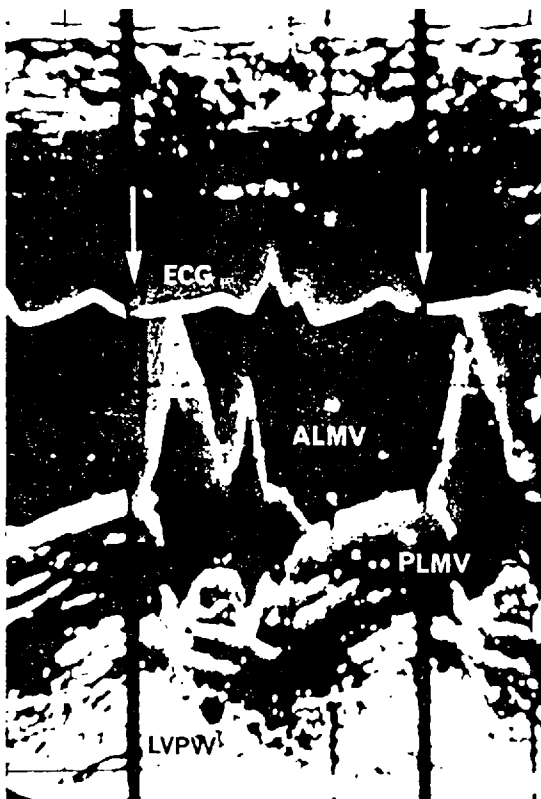


Figure 57. M-scan echogram showing the time marker (black line stressed by arrows) positioned at the T-wave of the electrocardiogram (ECG) which coincides with the end of mechanical systole (just before opening of the anterior and posterior mitral valve leaflets (ALMV, PLMV)). (LVPW=left ventricular posterior wall). see text.

that in this particular patient the end of the T-wave coincides with the end of mechanical systole. The time marker line interrupts the electrocardiogram at the end of the T-wave (arrow), then the closed mitral valve leaflets at the end of systole, just before the mitral valve leaflets open in diastole, and finally the left ventricular posterior wall is marked at the peak of the systolic anterior motion of the left ventricular posterior wall. The peak of the R-wave in the electrocardiogram does not coincide here with the mechanical end of diastole. In this patient a delayed B-point⁵¹ is shown, and the final closure occurs considerably later.

A different situation is shown in fig. 58. In this

patient the end of the T-wave does not coincide with the end of mechanical systole. The black time marker line indicates the correct timing of the gate for the end of the mechanical systole. The dotted lines indicate the electrical end of systole, which in this case occurs well after the mitral valve has begun to open.

Triggered B-scans produce a true cross-sectional image of the heart and it is important to insure that the same plane through the heart is scanned in all cases. This problem is much less acute in angiocardiology where a projectional image of the heart is displayed. For consistent and reproduceable results it was necessary that all inter-

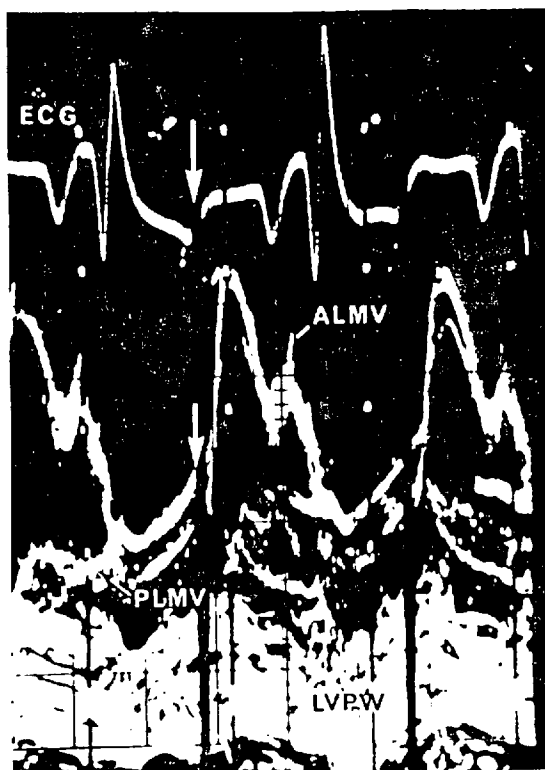


Figure 58. M-scan echocardiogram displaying the black time marker line at the end of mechanical systole, which in this patient does not coincide with the end of electrical systole. For further information see text and fig. 57.

nal landmarks, as described on p.64 , were simultaneously imaged and recognised within one plane.

Left ventricular volumes were calculated from single plane cineangiocardiograms performed in the RAO projection. The left ventricles were opacified with 50 ml of contrast medium, which was injected at 10 ml/sec by a rate controlled electro-mechanical injection pump. For larger ventricles larger volumes were used. The smallest and largest calculated volumes during the cardiac cycle were taken as end-systolic and end-diastolic volumes. Each cine film was projected by a Vanguard motion analyser, and

planimetry was performed electronically with a PCD trace reader, employing Simpson's rule of integration. These results are fed directly into an Olivetti P601 calculator programmed to give volumes in ml by the area-length method, as described by Dodge⁴³ and Kasser and Kennedy⁵² . In this formula the dimension of the long axis is also needed and we have consistently measured it from the origin of the posterior aortic root to the apex. The same apparatus and programme were utilised for both B-scan and angiographic volume determinations. This underlines the significance of the aorto-mitral transition zone as a landmark, particularly for B-scanning, which is important for the accurate delineation of the left ventricular area as shown in fig. 59.

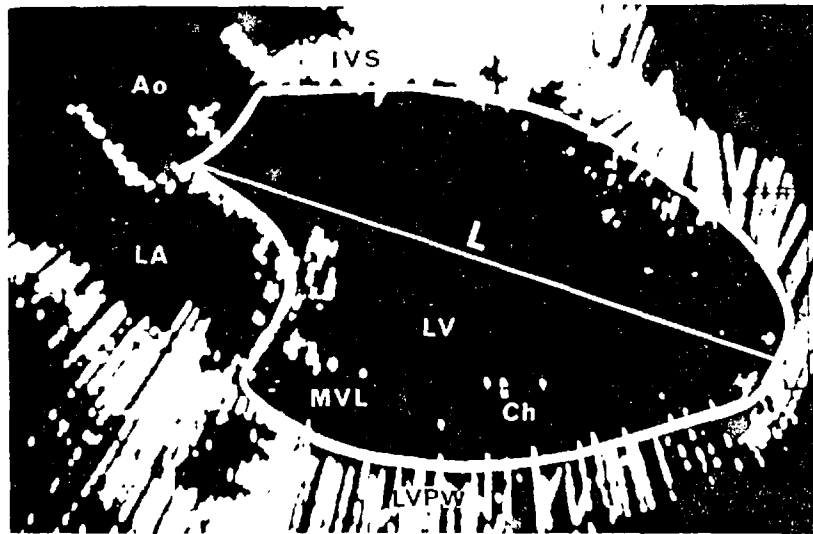


Figure 59. Triggered B-scan echocardiogram to illustrate the outline of the left ventricle (LV) for volume measurements (see text). (LA=left atrium, Ao=aortic root, IVS=interventricular septum, MVL=mitral valve leaflet, Ch=chordae tendineae, L=length).

The 20 adult patients in this study were all subjects undergoing left ventriculography for diagnostic purposes. The triggered B-scans and the angiograms could not, of course, be recorded simultaneously, but were almost all performed within 24 hours of each other. Selection was solely on the basis of the patients having both a satisfactory B-scan and a ventriculogram suitable for volume measurements. A number of patients (about 20%) had to be rejected as either their ventriculograms or their ultrasonograms were unsuitable for exact measurements because of ectopic beats, atrial fibrillation, or inability to define all the requisite landmarks in the B-scan. The final diagnoses of the patients included in this study are listed in table 1.

Diagnosis	No.(20)
Hypertrophic cardiomyopathy	5
Congestive cardiomyopathy	2
Coronary artery disease	3
Angina (normal coronaries)	1
Marfan's syndrome	1
Takayashu's syndrome, aortic regurgitation	1
Transposition of the great arteries	1
Aortic stenosis, aortic regurgitation	3
Restrictive cardiomyopathy	1
Constrictive pericarditis	1
Pericarditis	1

Table 1. Final diagnoses of the 20 patients included in this study.

C. RESULTS

The calculations for volumes and ejection fractions (EF) from the angio- and echograms are shown in table 2.

No.	ANGIO VOLUMES (ml)				TBS-VOLUMES (ml)			
	diast.	syst.	SV	EF(%)	diast.	syst.	SV	EF(%)
1	454	357	97	21	449	278	171	38
2	168	10	158	94	192	66	126	66
3	405	264	141	35	304	251	53	17
4	562	304	258	46	569	416	153	27
5	393	131	262	67	292	168	124	42
6	128	44	84	66	112	40	72	64
7	232	43	189	81	164	36	128	78
8	218	35	183	84	161	42	119	74
9	196	39	157	80	198	30	168	85
10	319	253	66	21	210	150	60	29
11	257	97	160	62	118	43	75	64
12	336	233	103	31	302	208	94	31
13	150	51	99	66	196	123	73	37
14	121	55	66	55	158	66	92	58
15	472	363	109	23	502	176	126	42
16	267	113	154	58	278	132	146	53
17	253	109	144	57	295	170	125	42
18	169	103	66	39	189	110	79	42
19	193	172	21	11	200	163	37	19
20	410	281	129	31	395	257	138	35

Table 2.

Angiographic and triggered B-scan (TBS) volumes were calculated with the area-length method from end-systolic and end-diastolic frames. Stroke volume (SV) was derived by subtracting end-systolic from end-diastolic volumes, and ejection fraction (EF) by dividing stroke volume by the end-diastolic volume.

The left ventricular volumes derived from the ultrasonograms were plotted against the angiographic volumes at end-systole and end-diastole in fig. 60. The correlation coefficient, r , is 0.88 ($P < 0.001$) and the regression equation is given by $y = 0.76x \pm 32$, with standard error of estimate, $s = 57$ ml. The correlation between the ejection fractions is shown in fig. 61

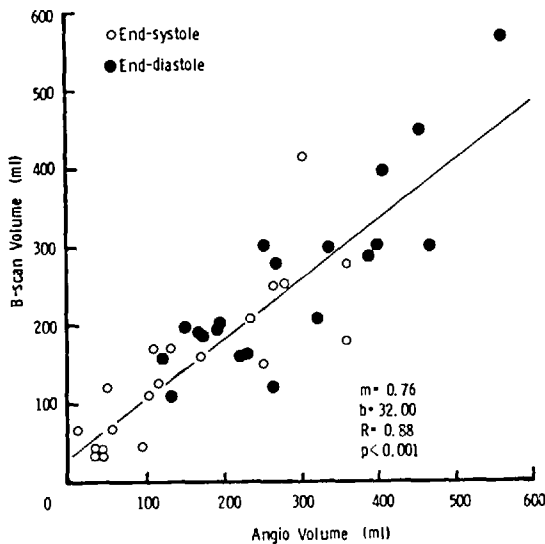


Figure 60. End-systolic and end-diastolic B-scan volumes are plotted against the corresponding angiographic volumes in ml. See text.

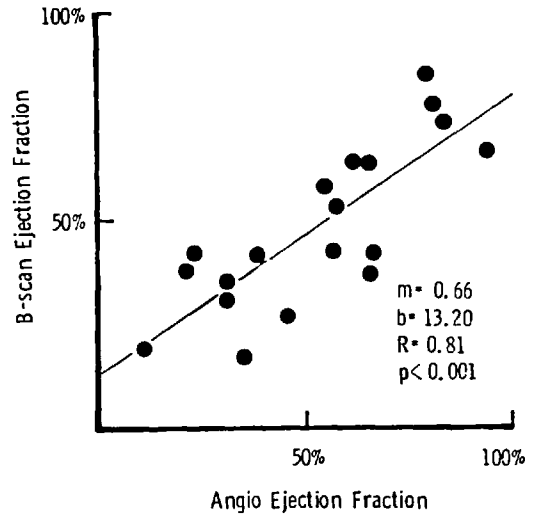


Figure 61. Angiographic and triggered B-scan left ventricular ejection fractions are plotted against each other. See text.

with $r = 0.81$ ($P < 0.001$), and the regression equation is given by $y = 0.66 \pm 13.2$, with $s = 11.5\%$.

D. DISCUSSION

Comparison of the above results with those of King et al.⁴¹ shows that similar accuracy is obtained for smaller volumes (< 250 ml); for larger volumes (up to 600 ml), although the scatter in the data becomes larger, the slope of the regression line is maintained quite close to the theoretically expected value in contrast to that of King et al.

The departure of the regression line slope from the expected one is almost certainly due to the circumstances that,

although the standard scanning plane is, in my opinion, reliably and consistently fixed, it does not necessarily give the maximal cross-sectional area of the left ventricle and the measured left ventricular area may therefore not be the appropriate one to use in the area-length formula. This point can be clarified only by a more systematic study involving a direct comparison of B-scan and true volumes. The scatter of the data points about the regression line is due to a variety of factors, the most important of which are discussed here.

The most obvious of the factors leading to data scatter is the essential difference between angiographic and B-scan techniques; the former produces a projection image, whereas the latter gives a true cross-section (see fig. 36, p. 54). Clearly the same plane is not imaged in both cases, but the errors are minimised by the choice of standard B-scanning plane and the right anterior-oblique position of the patient for angiography. Unfortunately this position can result in an apparent foreshortening of the angiographic projection image, as discussed on p. 61 (see also fig. 44 and fig. 45).

The magnification factor for the angiograms was determined only by comparing the width of the catheter on the cine film with its known diameter. The small scale of these measurements makes accuracy impossible. Furthermore the ultrasound scale is determined on an assumed mean velocity of ultrasound in tissue which differs from that in blood by up to 2% (leading to a volume error of at least 6%).

The angiographic area is a projection which ignores irregularities in chamber outline and includes trabeculae and papillary muscle within the cavity, whereas the echogram is not an instantaneous picture but gives an average over a large number of cardiac cycles.

The angiographic volumes are increased by the fluid injected into the ventricle to opacify it, producing stronger contractions according to Starling's law. This will result in artificially high end-diastolic and small end-systolic volumes. Patients undergoing B-scanning are not so affected

and are at rest compared with the stimulation and apprehension of angiocardiology. Another discrepancy may occur in patients with asymmetrical ventricles, particularly if either the scanning plane of the echogram or the projection of the angiogram does not display the abnormal segment in its entirety. However, in abnormalities like hypertrophic cardiomyopathy, ventricular aneurism, or coronary artery disease, the projected and ultrasonic images usually have a similar shape, suggesting that both techniques are subject to similar errors. In these cases, which constitute approximately 60% of our cases, the M-scan volume measurements are known to be unreliable.^{46, 50}

On consideration of the numerous factors leading to discrepancies between the angiographic and echographic volumes, it is almost surprising that the results correlate as well as they do. It is possible that the calculations from the echogram give a truer reflection of the real left ventricular volume than those obtained from the angiogram.

It is of interest to point out the advantages in our technique over that of King et al.: firstly, five landmarks, unless lying along a single line, will fix a single and reproducible plane. Only two landmarks, as used by King et al., will fix a line through the heart but not the orientation of the scanning plane through that line (see p. 64). Secondly, as pointed out above, the electrical phase of the cardiac cycle as indicated by the ECG does not necessarily coincide with the mechanical phase of the heart. For example: in aortic stenosis the end of the T-wave does not represent end-systole, since the mitral valve opens considerably later, whereas in myocardial failure mitral valve opening takes place before the end of electrical systole. Thirdly, the same method (single plane planimetry with the Olivetti calculator) was used for both the echographic and the angiographic volume calculations.

E. CONCLUSION

Two-dimensional echocardiography in spite of many possible

sources of error, appears to be a reliable method of measuring left ventricular volumes. It has the great advantage of being non-invasive, easily repeatable, and not unpleasant for the patient. It is likely to be more reliable in those conditions where the M-scan volume calculations are inaccurate, when the ventricle is large and irregular. With improvement in the technique, such as real-time visualisation of the complete ventricle, B-scan volume determinations will have an important place in the day-to-day assessment of cardiac function.

Part of this study has been reported on different occasions.^{16, 53, 55}

CHAPTER VIII

LEFT VENTRICULAR FUNCTION
BY ONE- AND TWO-DIMENSIONAL ECHOCARDIOGRAPHY
VERSUS ANGIOCARDIOGRAPHY

A. COMPARISON OF ONE- AND TWO-DIMENSIONAL ECHOGRAPHIC VOLUME CALCULATIONS

1. Introduction

When observing the correlations between triggered B-scan and angiographically determined volume measurements with a correlation coefficient of $r=0.88$ and $P<0.001$ (see fig. 60, p. 86), it appeared of interest to calculate the magnitude of the correlation coefficient between the M-scan, B-scan and angiographic volume data of the same patients in order to examine their relative association. One could also imagine that with the two-dimensional display of the left ventricular cavity a more exact short axis dimension might be obtained. If cubing this B-scan short axis dimension for volume assumptions gave a better correlation with the angiographically determined volumes than those from M-scan measurements, then this simple M-scan echographic index for functional parameters of the left ventricle would not be as questionable as generally assumed provided an optimal transverse diameter is captured with M-mode echocardiography.

2. Material and methods

Patients undergoing angiographic examinations of the left ventricle were investigated by triggered B-scan and M-scan echocardiography within 48 hours of the catheter study. Only some of the patients of the previous volume study were included in this one. The exact method for angiographic and B-scan echographic volume calculations with the area-length method are described earlier on p.82 . In addition the widest transverse diameters of the left ventricles from the triggered B-scans were determined at right angles to their long axes, which were drawn as a line from the posterior aortic root to the cardiac apex. The short axis diameter was cubed and so was the short axis dimension from the M-scan echocardiogram. End-diastole was measured at the peak of the R-wave of the

simultaneously recorded ECG, as the widest point of separation between the interventricular septum and the left ventricular posterior wall, and end-systole at the narrowest distance between them. Stroke volumes and ejection fractions were calculated, as previously described.⁴⁴

3. Results and discussion

The data obtained from M- and triggered B-scan echocardiography and angiocardiology are used to calculate parameters of left ventricular functions which are shown in table 3.

Sex	Angio volume				T.B.S. volume				M-scan volume (LVID ³)				T. B.S. short axis volume			
	ESVml	EDVml	SVml	E.F.%	ESV	EDV	SV	E.F.	ESV	EDV	SV	E.F.	ESV	EDV	SV	E.F.
D.W. f	26	161	135	84	40	140	100	71	56	113	57	50	33	110	77	70
D.O. m	66	119	53	45	170	260	90	35	50	76	26	34	125	215	90	42
H.K. f	110	280	170	61	144	276	132	48	77	144	67	47	175	315	140	44
T.C. m	110	190	80	42	166	217	51	24	140	268	128	48	238	312	74	24
W.C. m	87	132	45	34	123	195	72	37	88	143	55	38	64	157	93	59
T.C. m	264	405	141	35	197	261	64	25	272	380	108	28	238	313	75	24
J.B. f	112	189	77	41	110	190	80	42	140	225	85	38	64	195	131	67
S.C. m	350	570	220	39	235	384	149	39	79	194	115	59	342	510	168	33
J.S. f	63	180	117	65	33	82	49	60	30	85	55	65	30	50	20	40
T.R. m	113	267	154	58	136	302	166	55	125	245	120	49	194	436	242	56
H.R. m	357	454	97	21	278	449	171	38	190	730	540	74				
L.D. f	131	393	262	67	168	292	124	42	180	345	165	48				
T.P. m	42	185	143	77	44	128	84	66	40	112	72	64				
J.D. m	35	218	183	84	42	161	119	74	12	100	88	88				
R.C. m	97	257	160	62	43	118	75	64	121	184	63	34				

Table 3. Volume data obtained from angiograms, triggered B-scans (TBS), and M-scan echograms of 15 patients. (ESV, EDV=end-systolic, end-diastolic volume, SV=stroke volume, EF=ejection fraction, LVID³=left ventricular internal diameter cubed, m=male, f=female.)

The results of the various methods are correlated with one another and shown in figs. 62-69.

Many studies have shown that cubing the left ventricular internal diameter from the M-scan echogram is unreliable for volume calculations when the shape of the ventricle changes

its geometry^{46,50}. It occurred that a major reason for the discrepancy might be the fact that the M-scan beam might not scan along the exact short axis of the heart but in an oblique direction. The comparison of left ventricular volume calculations for end-systole and end-diastole from the angiograms and triggered B-scan echograms in fig. 62 shows that they correlate with a coefficient of $r=0.84$, $P<0.001$, very similarly to the volumes calculated by cubing the short axis of the ventricle from the triggered B-scan images ($r=0.83$, $P<0.001$ in fig. 63), as compared to the volumes calculated from the M-scan echocardiograms ($r=0.67$, $P<0.001$ in fig. 64).

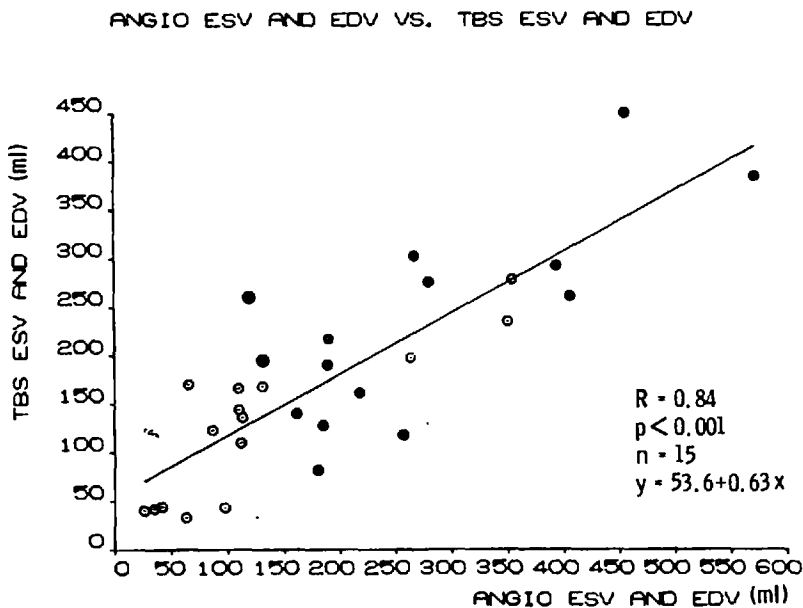


Figure 62.
End-diastolic and end-systolic (EDV, ESV) volumes obtained from triggered B-scanning (TBS) were plotted against the corresponding angiographic volumes. (See text).

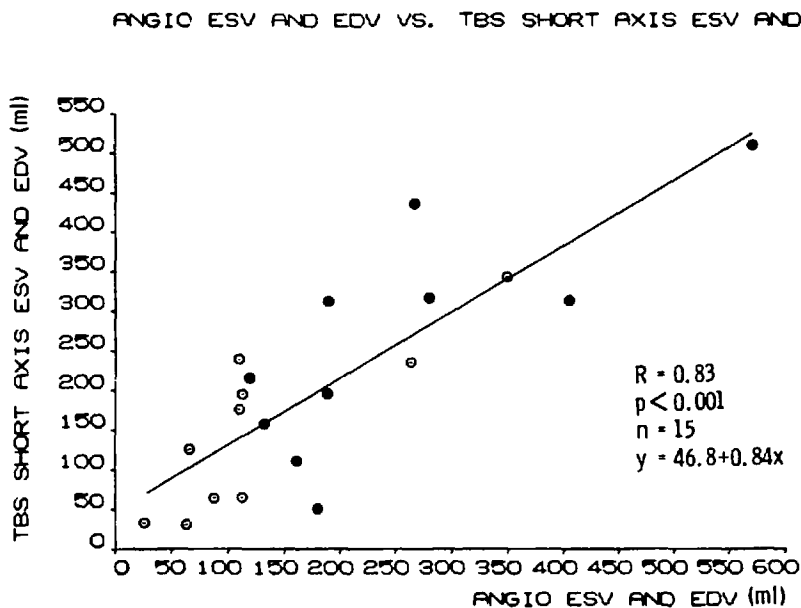


Figure 63.
Short axis dimensions from triggered B-scans (TBS) are cubed and the resulting end-systolic and end-diastolic volumes (ESV, EDV) are plotted against the corresponding angiographic volumes. (See text).

ANGIO ESV AND EDV VS. M-SCAN ESV AND EDV

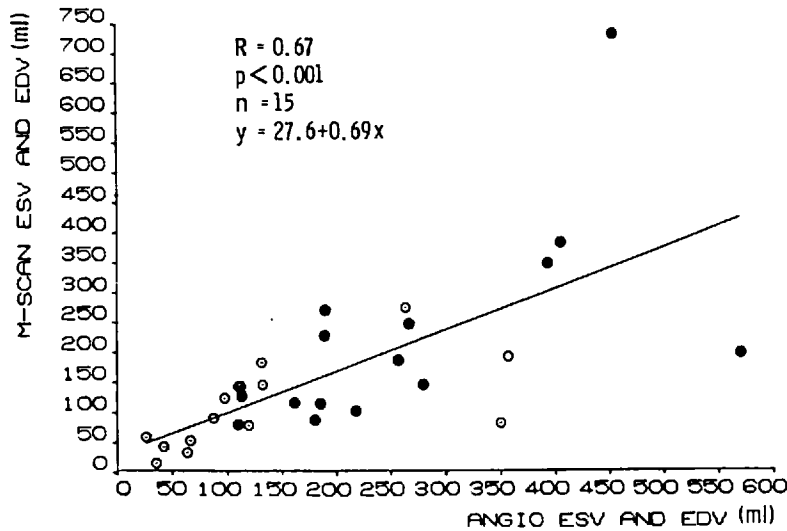


Figure 64.
End-systolic and end-diastolic volumes (ESV, EDV) are calculated from the left ventricular internal diameters of the M-scans and plotted against the corresponding angiographic volumes. (See text.)

This may indicate that M-scan volume calculations may not be so superfluous, particularly for smaller ventricles (up to an end-diastolic volume of 300 ml or less)⁵⁵, and also if the beam direction was controlled for example by two-dimensional ultrasonic display. This could encourage further research with real-time B-scanning for non-invasive functional parameters of the heart. However, since all calculated stroke volumes did not correlate well with the angiographically determined stroke volumes (see figs. 65-67), one has to question

ANGIO SV VS. TBS SV

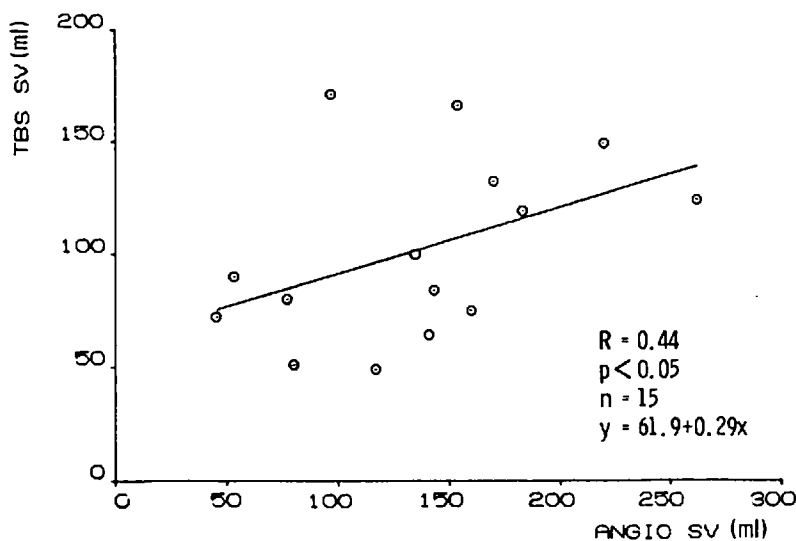


Figure 65.
Stroke volumes (SV) are calculated from the triggered B-scans (TBS) and plotted against the corresponding angiographic SV. (See text.)

ANGIO SV VS. M-SCAN SV

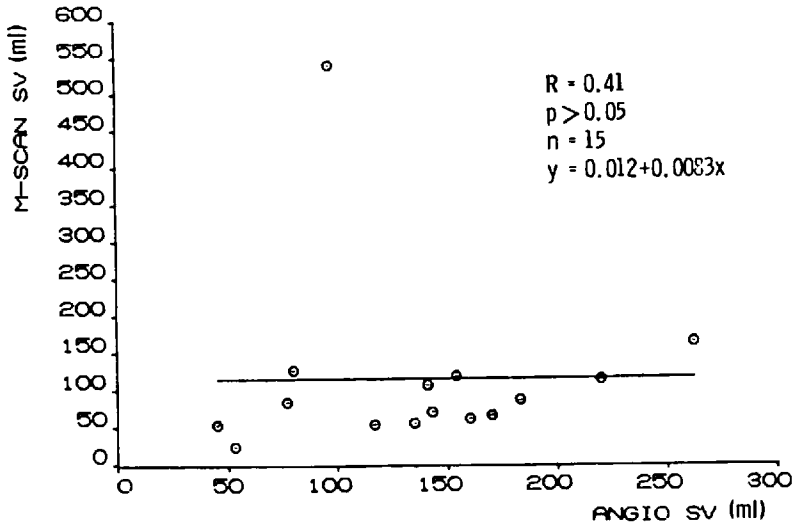


Figure 66.
Stroke volumes (SV) are calculated from the M-scans and angiograms, and plotted against each other. (See text).

ANGIO SV VS. TBS SHORT AXIS SV

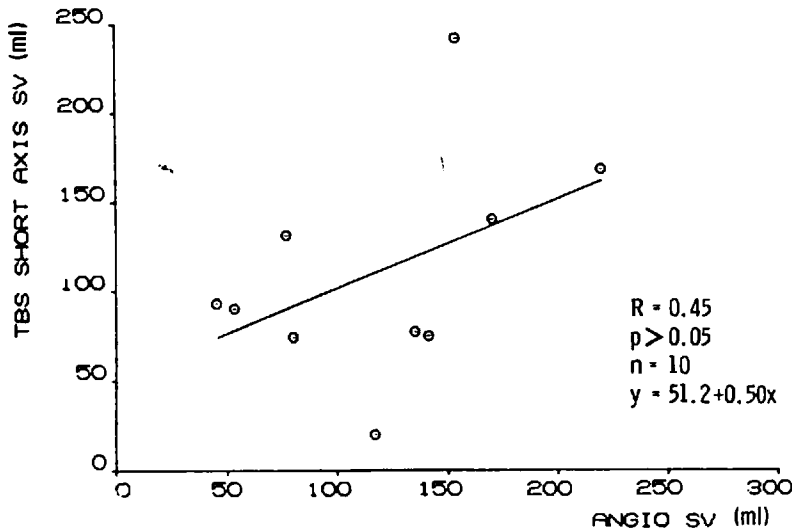


Figure 67.
Stroke volumes (SV) are calculated from the cubed short axis of triggered B-scans (TBS) and angiograms to be plotted against each other.

the significance of the left ventricular volumes as a functional indicator on the one hand, and of the stroke volume itself on the other hand. They may have relevance only to calculation of ejection fractions, which appear to be a more reliable measure of left ventricular function because they are independent of the formulae used for volume calculations. The ejection fractions calculated from the short axis

of the triggered B-scans, using the method of cubing the internal diameter, did not correlate well with the angiographically determined ejection fractions (see fig. 68). Only ejection fractions calculated with the area-length method correlated well ($r=0.85$, $P<0.001$) in this series (see fig. 69).

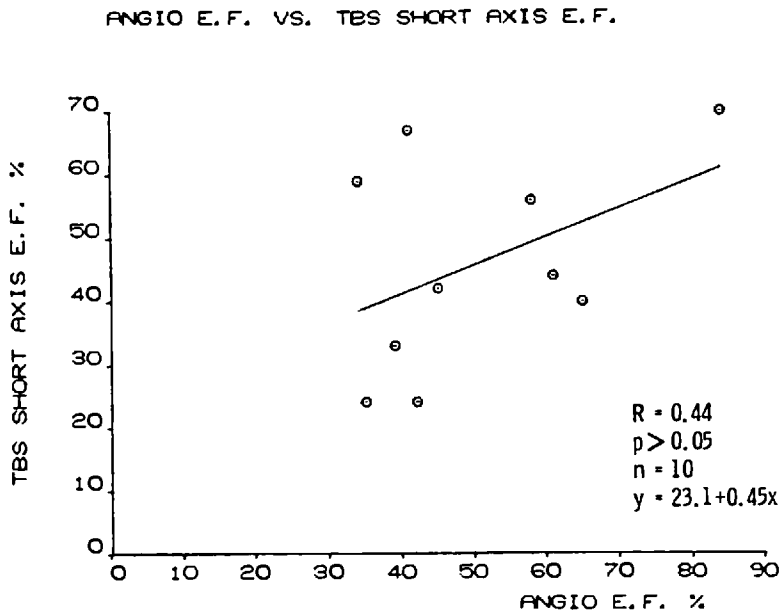


Figure 68.
Ejection fractions (EF) are calculated from the cubed short axis of triggered B-scans (TBS) and from angiograms, and plotted against each other.

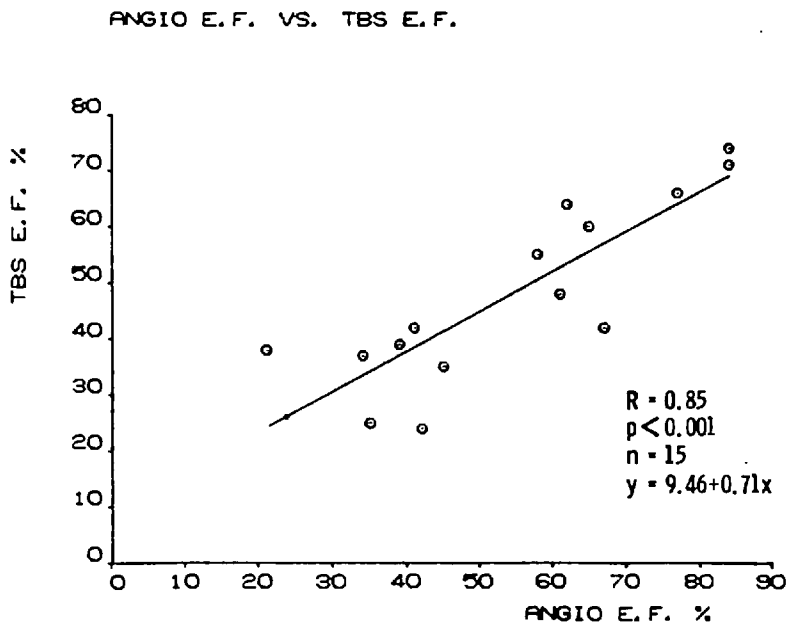


Figure 69.
Ejection fractions (EF) are calculated from Triggered B-scans (TBS) to be plotted against the angiographic ejection fractions.

4. Conclusions

The results shown indicate that two-dimensional methods may be the non-invasive diagnostic tool of choice for functional cardiac parameters in the future. This may apply particularly to real-time B-scanning, mainly because individual gain setting controls during the build up of the triggered B-scans may influence the size of the finally obtained area of the left ventricle considerably in comparison to an overall gain control in real-time B-scanning, and secondly because the mean value of the triggered B-scan area does not allow beat to beat changes to be evaluated with this method. Furthermore it is much too time-consuming to perform multiple triggered B-scans around end-systole or end-diastole in order to select the largest volume at the exact moment of end-diastole and the smallest for end-systole respectively.

It can be concluded that functional indices from the M-scan echogram may give a good indication of left ventricular contraction with volumes of 300 ml or less at end-diastole, but that better assumptions in larger or distorted left ventricles may be obtained with two-dimensional echocardiography.

B. INTER-OBSERVER DIFFERENCES IN ANGIOGRAPHIC VOLUME CALCULATIONS

In order to examine the meaningfulness of the statistical analyses of the previous chapter when correlating the angiographically and echographically determined volume measurements (with angiography as the reference method), two independent observers have calculated left ventricular volumes, stroke volumes, and ejection fractions from the angiograms of 14 patients, using the area-length method.⁵²

- Results

The data obtained by the two observers are shown in Table 4, The results of the planimetred areas, the long axis measurements, and finally the end-systolic and end-diastolic volumes,

		A N G I O																				
		Long axis				Planimetred area				Volume												Diagnosis
Initials	Sex	L _S (cm)		L _D (cm)		A syst. (cm ²)		A diast. (cm ²)		Syst. Vol. (ml)		Diast. Vol. (ml)		SV (ml)		E.F. %						
		I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II					
1	H.R.	m	12.2	11.9	13.7	12.2	71.7	62.0	85.5	78.6	357	274	449	429	92	155	20	36	Marfan			
2	W.C.	f	8.8	9.8	13.2	11.8	10.3	23.0	51.2	52.0	10	46	168	194	158	148	94	76	HCM			
3	S.C.	m	10.9	10.6	12.5	11.8	63.9	56.6	84.1	76.8	264	257	405	424	141	167	35	41	COCM			
4	S.C.	m	12.7	12.4	15.1	15.1	64.0	70.3	99.0	108.7	304	339	562	665	258	326	46	49	MR,AR			
5	D.D.	m	9.9	10.4	13.2	11.3	39.2	43.9	78.1	62.7	131	156	393	294	262	138	67	47	Sub.AS			
6	T.P.	m	4.8	10.4	11.8	11.8	15.7	24.2	42.3	44.3	44	48	128	141	84	93	66	66	HCM			
7	R.D.	f	6.9	6.8	9.5	9.2	18.8	20.6	51.1	44.1	43	53	232	180	189	127	81	71	HCM			
8	J.D.	m	5.9	9.1	13.7	11.9	15.7	17.5	59.2	47.6	35	29	218	162	183	133	84	82	HCM			
9	D.W.	f	5.6	5.2	12.0	10.3	16.1	13.2	52.7	41.8	39	29	196	144	157	115	80	80	HCM			
10	H.K.	f	10.6	8.5	11.0	9.5	62.7	38.6	72.1	53.9	253	149	319	259	66	110	21	42	COCM			
11	R.C.	m	9.8	7.1	11.2	10.1	33.4	20.3	58.4	44.4	97	49	257	165	160	116	62	70	Restr.peric.			

Table 4. The measurements of long axes, planimetred areas, and calculated volumes are obtained by two independant observers (I, II). (L_S, L_D= long axis in systole and diastole, A_{syst} and A_{diast}=systolic and diastolic areas, SV=stroke volume, EF=ejection fraction, HCM=hypertrophic cardiomyopathy, COCM=congestive cardiomyopathy, MR and AR=mitral and aortic regurgitation, m=male, f=female)

stroke volumes, and ejection fractions of the two observers were compared as shown in figs. 70-74. The correlation coef-

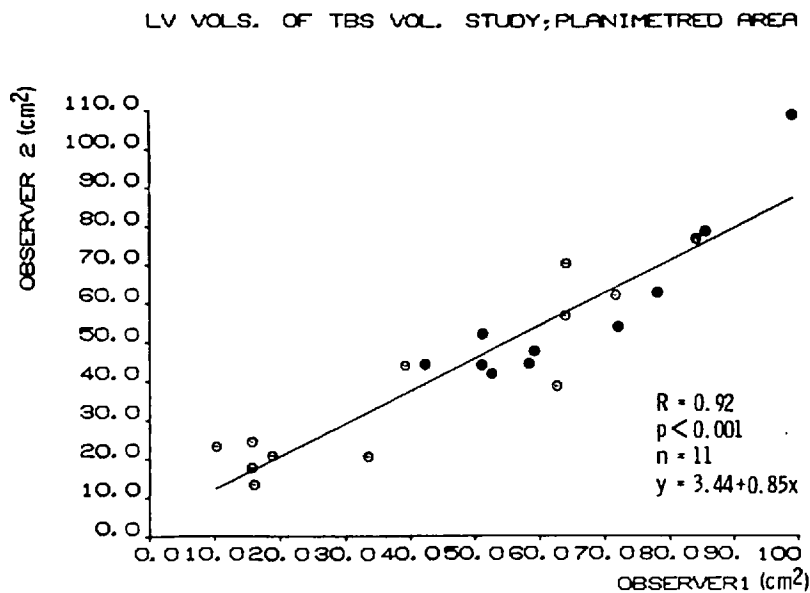


Figure 70.
The planimetred areas of cineangiograms are calculated by 2 independant observers. (See text)

LV VOLS. OF TBS VOL. STUDY; LONG AXIS

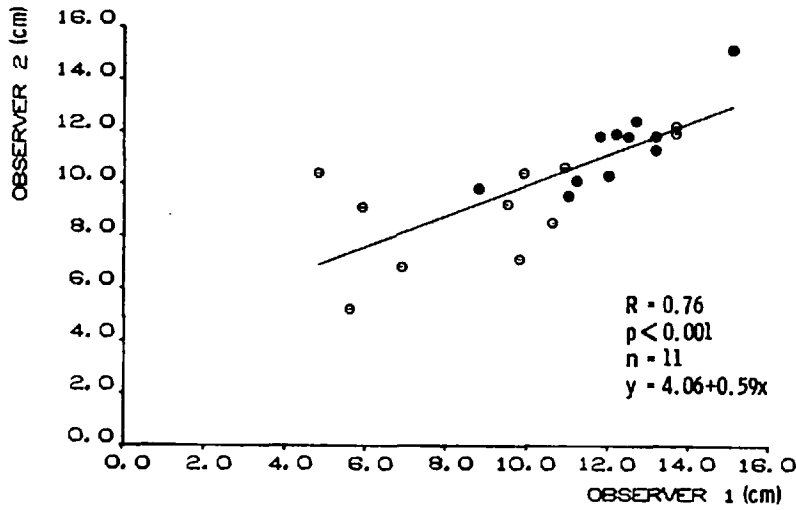


Figure 71.
The long axes are measured from cineangiograms by 2 independent observers. (See text)

ANGIO VOLUME CALCULATION BY 2 OBSERVERS

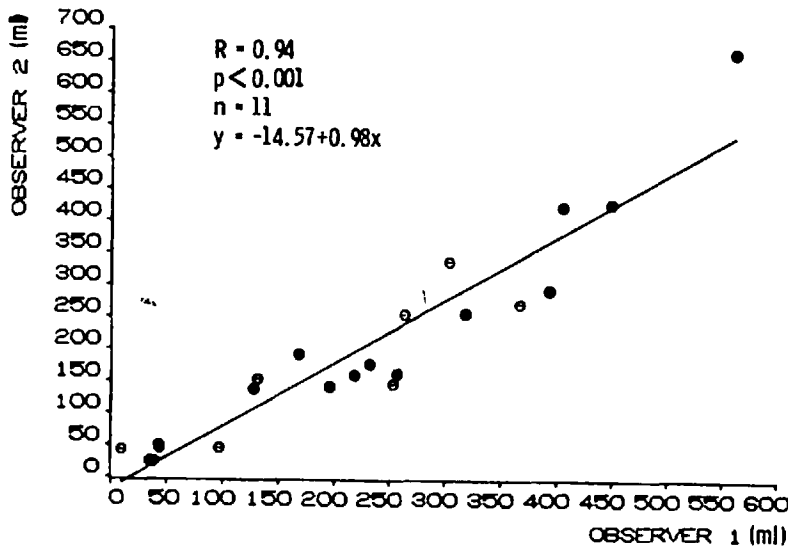


Figure 72.
Angiographic volumes calculated by 2 independent observers with the area-length method.

ANGIO STROKE VOLUME CALCULATIONS

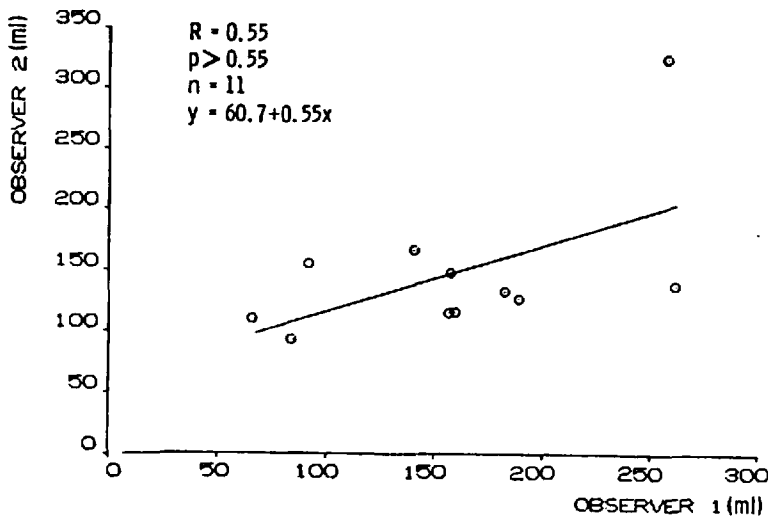


Figure 73.
Angiographic stroke volumes calculated with the area-length method by 2 independent observers. (See text).

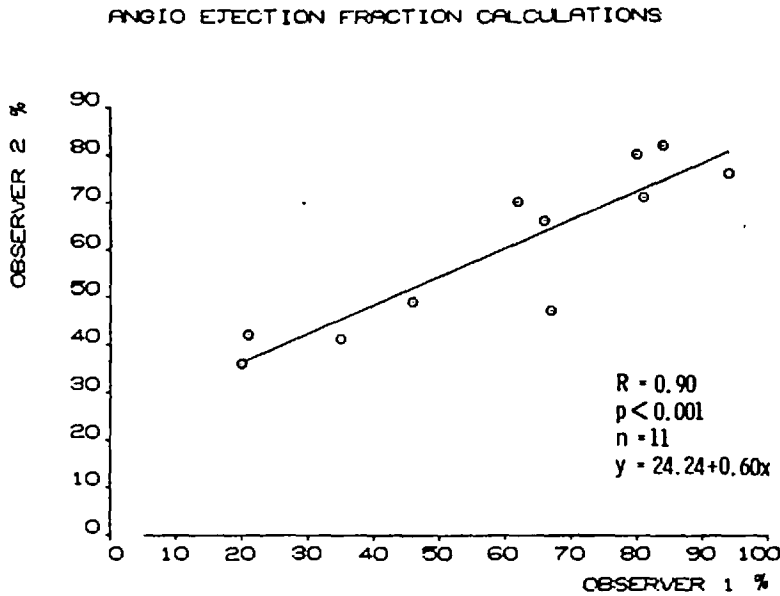


Figure 74.
Angiographic
ejection frac-
tions calculated
by 2 independant
observers. (See
text).

ficients ranged from $r=0.55$ to $r=0.94$, which means for some measurements that the two-dimensional functional parameters are in some instances as good as the calculations used by the reference method. The correlation coefficients were all significant except for stroke volume (fig. 73), which confirms that this parameter is an unreliable index of left ventricular function. A simple reason may be that the more a ventricle dilates the less amplitude of motion is required to maintain a given stroke volume.

Despite the significant correlations with the rest of the parameters it may be obvious that even our reference method is probably very crude to quantitate left ventricular function, due to the same factors given in the earlier discussion. There is, however, a hope that real-time B-scanning may in the future give a better indication of left ventricular function, since it represents a true cross-section through the heart at any desired plane, as compared to the limited projectional planes of angiography, and it also allows beat by beat analysis of at least 16-30 frames per second at the moment.

CHAPTER IX

APPLICATION OF TRIGGERED B-SCAN ECHOCARDIOGRAPHY
FOR IMAGING MORPHOLOGICAL CHANGES IN THE HEART

In the initial stage of developing triggered B-scan echocardiography by outlining the left ventricular cavity for volume measurements, it was hoped that this method could also be of some use for diagnosing heart disease by showing altered structural relationships within the heart. A few examples may illustrate the possible usefulness of this technique.

A. MITRAL STENOSIS

Fig. 75 is an example of a patient with mitral stenosis, showing a restricted separation of the thickened mitral valve leaflets in an end-diastolic frame. When we compare the rela-

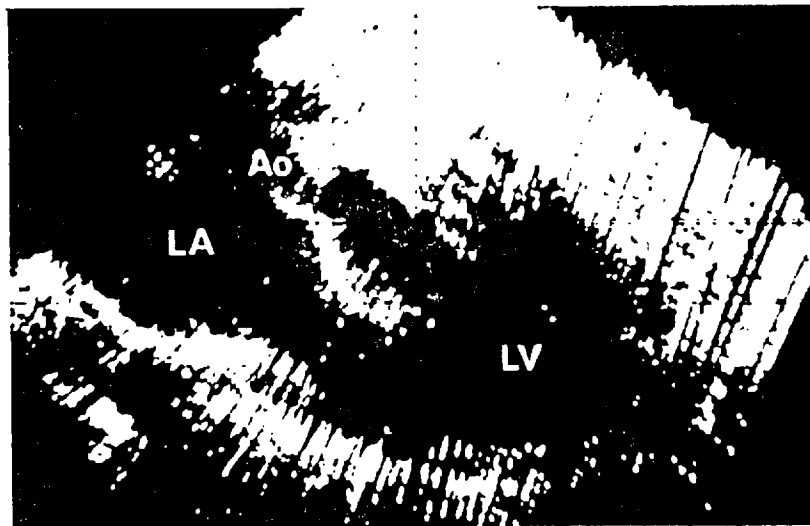


Figure 75. Triggered B-scan echocardiogram of a patient with moderate mitral stenosis. This end-diastolic frame shows an enlarged left atrium (LA) and left ventricle (LV) and a reduced separation of the thickened leaflets at orifice level. (See text).

tionship between left atrial and left ventricular sizes with those in normals (see fig. 59, p. 83), it is obvious that both are enlarged as seen in mixed mitral valve disease. Furthermore the anterior border of the left atrium is, as often observed, ill-defined, and the reason for this is that in some cases this anterior border is pushed into the left ventricular outflow tract which is nearly obliterated in

diastole. It was found that this actually represents a very mobile upper part of the anterior mitral leaflet which could be observed with different degrees of mitral valve thickening and narrowing at orifice level. Thus it became clear that anterior leaflet mobility does not necessarily allow conclusions as to the severity of mitral stenosis. This was later confirmed by real-time B-scan echocardiography.⁵⁶

Experience has also shown that the thickness of the mitral leaflets in the scans depends very much on the gain settings during the scanning procedure. This is also partly true for M-scanning, but with both techniques one can control the settings in relationship to other known structures visualised during the sweep by the brightness of their display and the relative density of, for example, the interventricular septal or left ventricular posterior wall echoes. This, however, proved much more difficult with triggered B-scanning. The difficulties are overcome today with real-time B-scanning, which gives also more functional information.

B. VENTRICULAR SEPTAL DEFECT

Fig. 76 shows the typical M-scan echographic finding in high

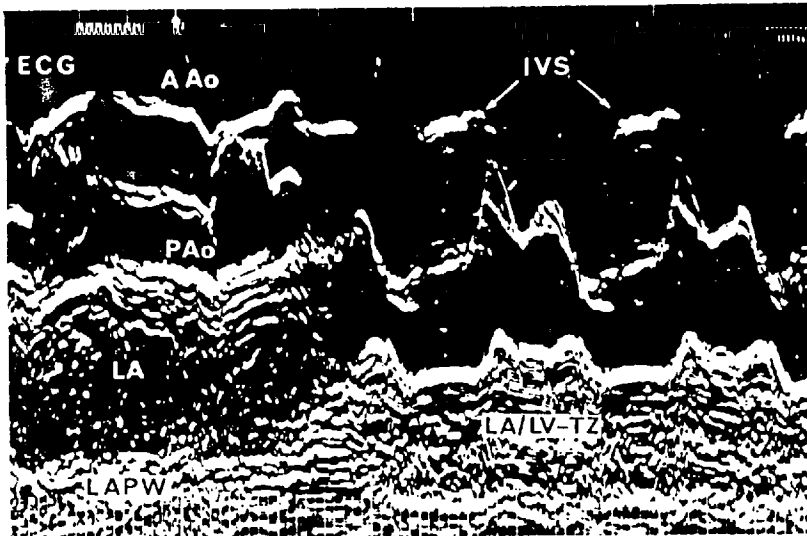


Figure 76. M-scan of a patient with a membranous ventricular septal defect, showing the typical interruption of the aorto-septal transition zone with intact aorto-mitral continuity. (ECG=electrocardiogram, AAo, PAo=anterior and posterior aortic root, IVS=interventricular septum, ALMV=anterior leaflet of the mitral valve, LA=left atrium, LAPW=left atrial posterior wall, LA/LV-TZ=transition zone between left atrium and left ventricle).

By courtesy of Tiong Hai Koh, cardiology technician from Singapore.

membranous, supracristal ventricular septal defect with the aorto-mitral transition zone as a continuous echo-line on strip chart recording, while anteriorly the aorto-septal transition zone is interrupted. This can also be demonstrated on Polaroid recordings, as shown in fig. 77 where the sweep from the aortic root (Ao) towards the left ventricular apex is carried out relatively fast with a slow recording speed of the storage oscilloscope. The arrow indicates the interruption of the normally continuous aorto-septal transition zone.

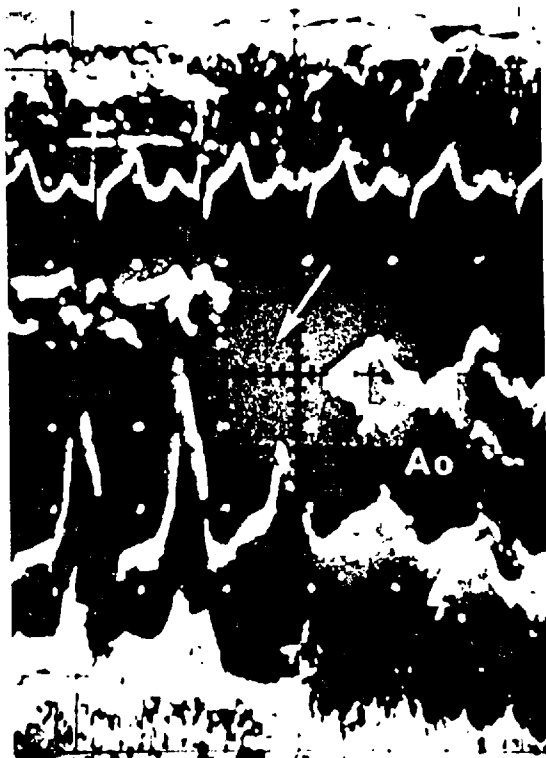


Figure 77. Another patient with a membranous ventricular septal defect (arrow), showing that the same features as in fig. 76 can be recorded on Polaroid paper.

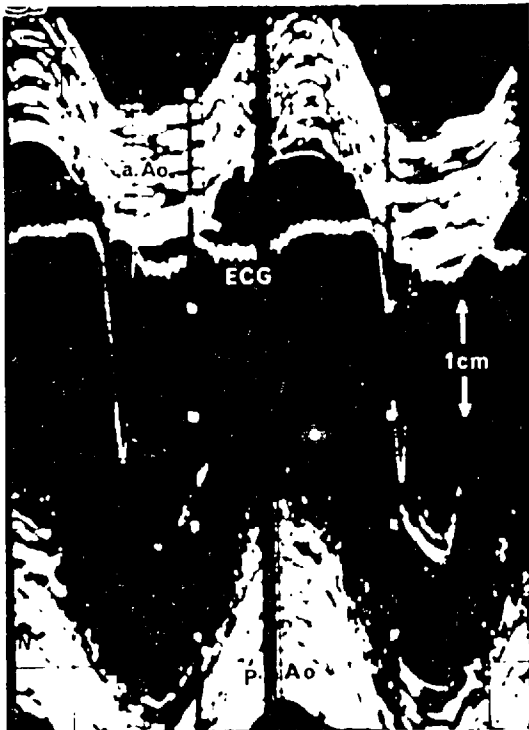
The advantage of the two-dimensional display of a defect is seen in fig. 78 where the aorto-mitral transition zone is nearly completely continuous while the thickened interventricular septum above shows a real defect. The size of this defect (see fig. 77) depends on the time the transducer rests in the particular position where no septal echoes are encountered, while triggered B-scan echocardiography provides a true anatomical relationship, and thus visualises its exact position.

The size, as discussed before, unfortunately depends again on the gain settings during the triggered B-scanning procedure. Another source of erroneous size measurements may lie in oblique scanning directions of the single beam from different positions on the chestwall. An oblique view of a defect will produce a narrower echo free space in the recorded septum. In a compound triggered B-scan various oblique directions are superimposed and may result in a summation of this error.



Figure 78. Two-dimensional display of a ventricular septal defect (arrow) with the triggered B-scanning technique allows a spatial appreciation of the altered anatomy of the heart. (AO=aortic root; RV, LV=right and left ventricles). See text.

C. AORTIC ROOT ANEURISM



The M-scan echographic examination of a 19-year-old patient with Marfan's syndrome initially showed no aortic cusps and only a slightly enlarged aortic root diameter, as seen in fig. 79. But the aortic walls were in fact considerably thickened. The conventional B-scan, as shown in fig. 80, was initially

Figure 79. M-scan from a patient with an aortic root aneurism, showing an aortic root diameter of 4.3 cm and thickened aortic walls. (aAo, pAo=anterior and posterior aortic root).



Figure 80. Conventional B-scan of the patient in fig. 79. The diagnosis of aortic root aneurism was not made until a triggered B-scan was carried out. (For orientation see fig. 51 and text).

confusing with its normal aortic root internal diameter. Structures 1 and 2 were first interpreted as anterior and posterior aortic walls. Only the triggered B-scan, as shown earlier in fig. 51, p. 70, clearly visualised the diverging and tremendously thickened aortic root wall 1 and 3, characteristic of an aortic aneurism. One can also see the aortic cusps incompletely closed in diastole, confirming the

findings of aortic regurgitation on auscultation. These cusps are blurred in the conventional B-scan and form the echo complex 2 which was first misinterpreted as posterior aortic root. The left ventricle is enlarged and the aortic root deformity was later confirmed by angiography, as shown in fig. 81. A subse-



Figure 81. Angiocardiogram of the patient in figs. 79-82, showing a huge aortic aneurism.

quent M-scan, performed after the triggered B-scan in the same session, shows a different aortic root diameter at aortic valve level, as seen in fig. 82.

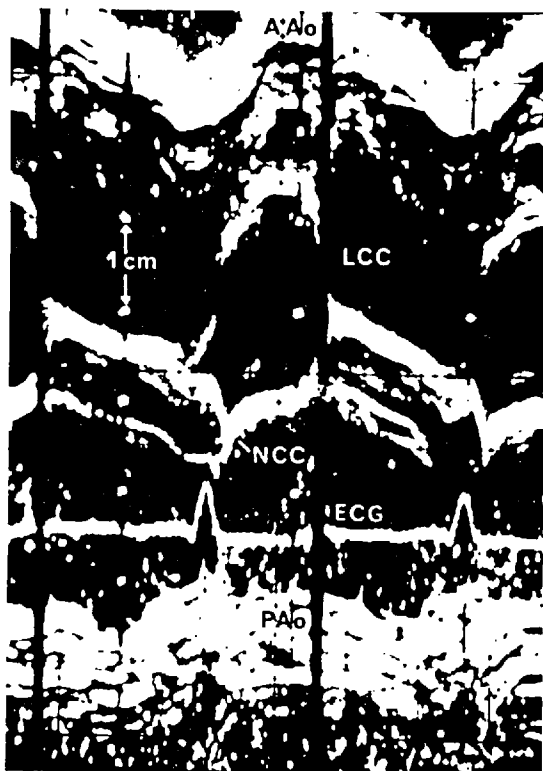


Figure 82. M-scan of the patient in fig. 79 showing an increased internal diameter at aortic valve level. (LCC, NCC=left and non coronary aortic cusps, AAo, PAo=anterior and posterior aortic root). See text.

Thus it appears that with M-scanning equipment alone, the diagnosis of such an aneurism can be missed if one does not perform a high sweep within the aortic root during examination in order to visualise the areas above and below aortic valve level. Triggered B-scanning was clearly able in this case to show the exact extent of this particular cardiac lesion, and helped us to develop a better understanding of the limitations of M-scanning techniques and how to overcome them.

D. LEFT VENTRICULAR ANEURISM

Most difficulties were encountered in patients with left ventricular aneurisms. Very often the left ventricular cavity looked normal in shape, as seen for example in fig. 83, and the angiogram revealed a huge apical aneurism. The cavity below the left ventricular posterior wall was initially believed to represent the aneurismal sack, and the normal shape of the left ventricle was explained by the cross-sectional plane scanning through the intact part of the left ventricular wall beyond the opening into the aneurism. A more likely ex-



Figure 83. Triggered B-scan of a patient with an apical left ventricular aneurism. The echo free area below the left ventricle (LV) may be a reverberation artefact, and not the aneurism. (Ao=aortic root, LA=left atrium). See text.

planation is that the aneurism was not envisaged in this cross-sectional plane and that these posterior echoes are in fact double echoes produced by reverberation, which in my experience are always found in patients with pericardial or pleural effusion. An example of an anterior left ventricular aneurism is seen in fig. 84. Although the acoustic properties

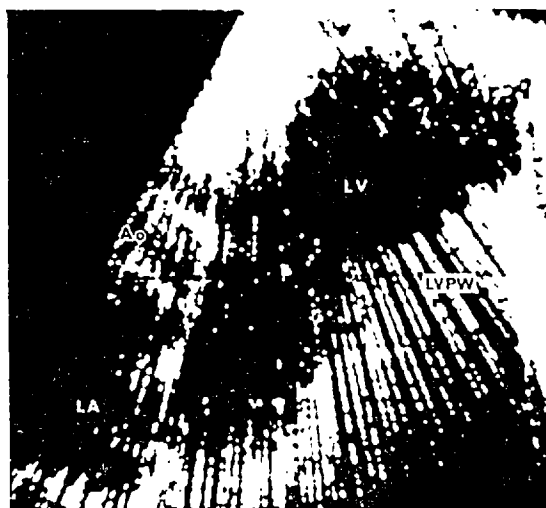


Figure 84. Triggered B-scan of a patient with an anterior left ventricular aneurism. For orientation see fig. 83.

were very difficult in this patient, one can see that the more apical part of the left ventricular anterior wall exhibits an unusual bulge towards the chestwall and this was confirmed by left ventricular angiography.

It was concluded from this study that left ventricular aneurisms are not reliably diagnosed either by M-scan or by triggered B-scan echocardiography. The double echoes, however, seen with both techniques, proved to be a reliable indication of pericardial and/or pleural effusion, as described later.

E. PERICARDIAL AND PLEURAL EFFUSION

The multiple echoes reported above as having been observed behind the left ventricular posterior wall in patients with left ventricular aneurisms were investigated further. These echoes are a prominent feature and are seen over a wide range of scanning planes and angles. Since none of the patients proved to have an aneurism during left ventricular angiography, another explanation had to be found. A group of 20 otherwise unselected patients in whom these posterior echoes could be observed during B- or M-scanning were investigated and the diagnoses are shown in table 5.

No. of patients	Diagnosis
3	coronary artery disease
3	mixed aortic valve disease
3	mixed mitral valve disease
3	pericarditis
2	hypertrophic cardiomyopathy
2	congestive cardiomyopathy
1	transposition of great arteries
1	constrictive pericarditis
1	ankylosing spondylitis
1	scleroderma

Table 5. Diagnoses of 20 unselected patients in whom echoes were observed far behind the left ventricular posterior wall and moving in phase with it. All of these patients were in fact found to have pericardial effusions.

In all of these patients M-scan echocardiography showed clear signs of pericardial or pleural effusions of various magnitudes. In some of them this was not immediately evident but clearly seen when specifically searched for. Fig. 85 demon-

strates with the continuous sweep technique posterior echoes which moved synchronously with the left ventricular posterior wall structures.

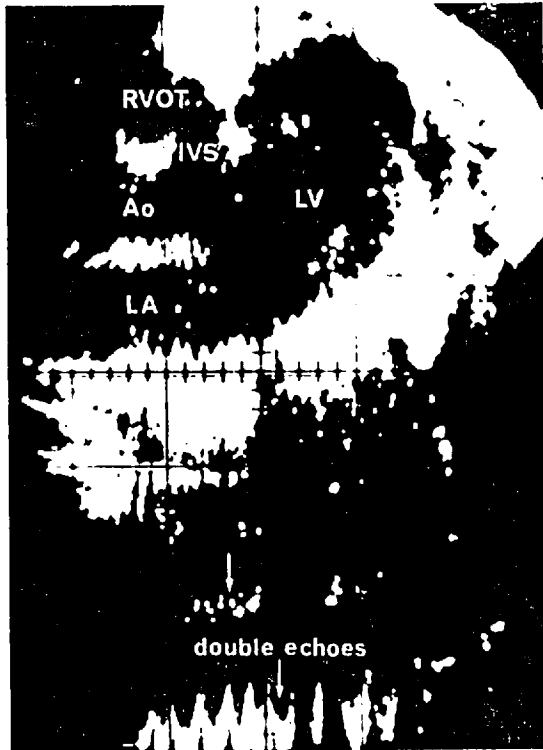


Figure 85. In this continuous B-scan sweep posterior echoes behind the left ventricle appear as duplication of the left ventricular posterior wall (see arrows). (RVOT=right ventricular outflow tract, IVS=interventricular septum, Ao=aortic root, LA, LV=left atrium and ventricle).

The same phenomenon can also be observed and demonstrated with M-scanning, as shown in a fast and in a slow sweep in figs. 86 and 87. The more exact timing of motion on the M-scans allows a differentiation of the virtual images, which may be a reflection of the subvalvular apparatus or the left ventricular posterior wall.

It was therefore concluded that these far echo structures are due to reverberation within the space provided by pericardial or pleural fluid. Since the recognition of small amounts of effusion is sometimes difficult these posterior echo structures may be taken as an indication of effusion and encourage the examiner to prove this with appropriate gain settings. This diagnostic feature has subsequently been proven to be present in real-time B-scanning as well and

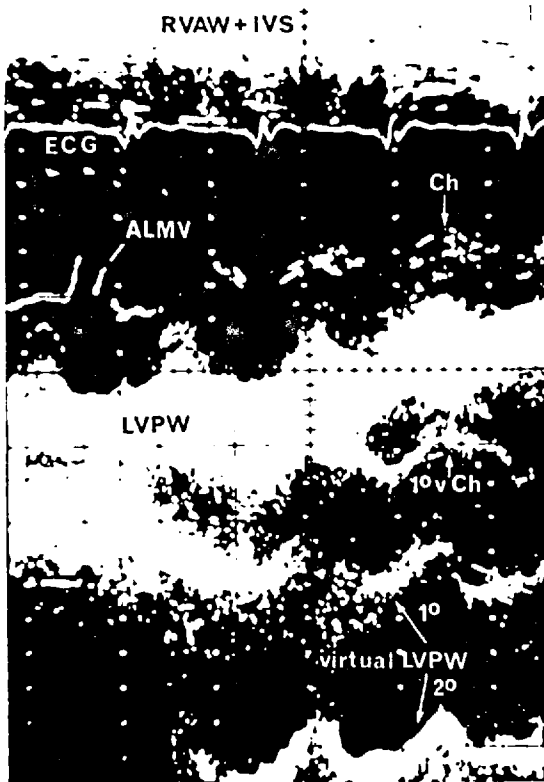


Figure 86. M-scan sweep of the patient in fig. 85, showing the same posterior echoes. (RVAW=right ventricular anterior wall, ALMV=anterior leaflet of the mitral valve, vCh=virtual chordae, LVPW=left ventricular posterior wall). For further orientation see fig. 85.

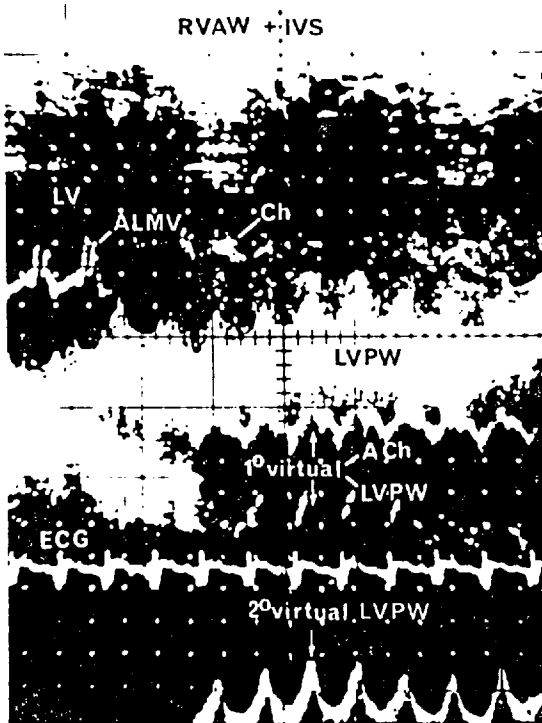


Figure 87. M-scan of the same patient as in figs. 85 and 86, showing virtual chordae and left ventricular posterior wall echoes. For orientation see figs. 85 and 86.

allows an instant diagnosis of pericardial or pleural effusion to be made. In order to be able to see this feature one has to reduce the scale of echo display on the screen before starting to scan such patients.

F. HYPERTROPHIC CARDIOMYOPATHY

M-scan echographic studies have shown already in 1973 that the 'typical' complete and incomplete systolic anterior motion ('SAM') of the mitral valve echo structures could be increased or decreased deliberately by changing the direction of the single ultrasonic beam. These structures could also be visualised in patients in whom no mitral regurgitation could be detected during selective left ventricular angiography. If 'SAM' structures were indeed a representation of mitral valve re-opening, as was believed at that time, then mitral regurgitation should be a consistent finding in all patients with this M-scan echographic feature. Other M-scans of our patients sometimes showed chordal structures and mitral valve leaflet echoes superimposed, and the former in continuity with the characteristic 'SAM' structures. This will be shown and discussed later in the chapter 'Hypertrophic cardiomyopathy in real-time B-scanning', p. 118. At this point I started doubting that 'SAM' was produced by the tips of the mitral valve leaflets and that the anterior leaflet plays a major role in the mechanism of left ventricular outflow tract obstruction in hypertrophic cardiomyopathy.

Triggered B-scan echocardiography was the first possibility for us to gain additional information by a two-dimensional ultrasound method. The first findings allowed the distinction between two types of septal hypertrophy. One type is characterised by an upper septal bulge (USB) with the main hypertrophy in the upper third of the interventricular septum, as seen in fig. 88. The other type is characterised by a mid-septal bulge, as seen in fig. 89. The latter scan shows thickened mitral valve leaflets and chordae tendineae leading into prominent papillary muscles. The size of the left ventricular outflow tract (LVOT) in our patients can be clearly visualised, and the example in fig. 90 of another patient with hypertrophic cardiomyopathy shows how high up in the outflow tract the septal hypertrophy can be located. The size of the outflow tract did not determine the size of left ventricular outflow tract obstruction.

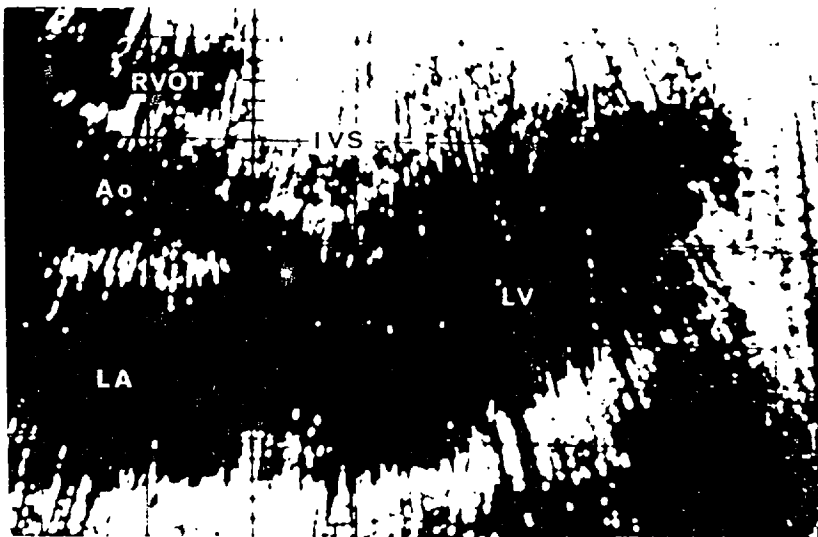


Figure 88.
Triggered B-scan
of a patient with
hypertrophic car-
diomyopathy show-
ing an upper sep-
tal bulge. (RVOT=
right ventricular
outflow tract, Ao
=aortic root, LA,
LV=left atrium
and left ventricle.

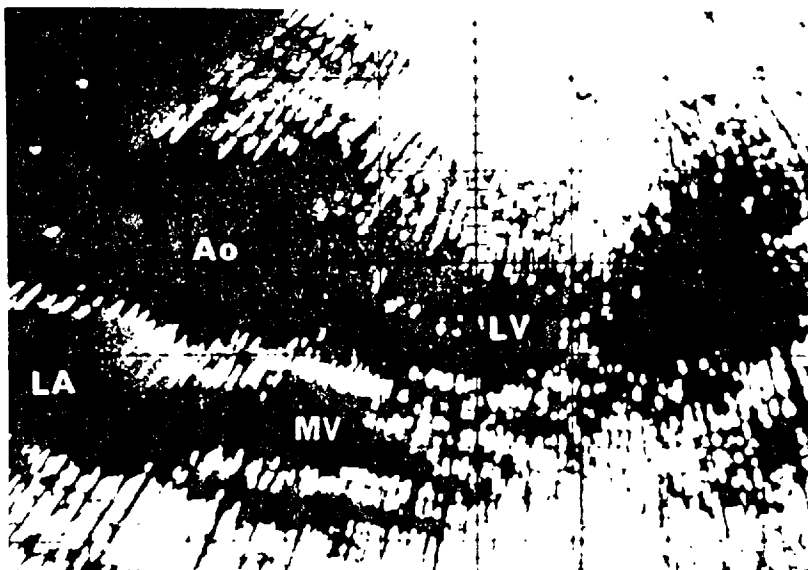


Figure 89.
Triggered B-scan
of another patient
with hypertrophic
cardiomyopathy
showing a mid-
septal bulge. (For
orientation see
fig. 88).

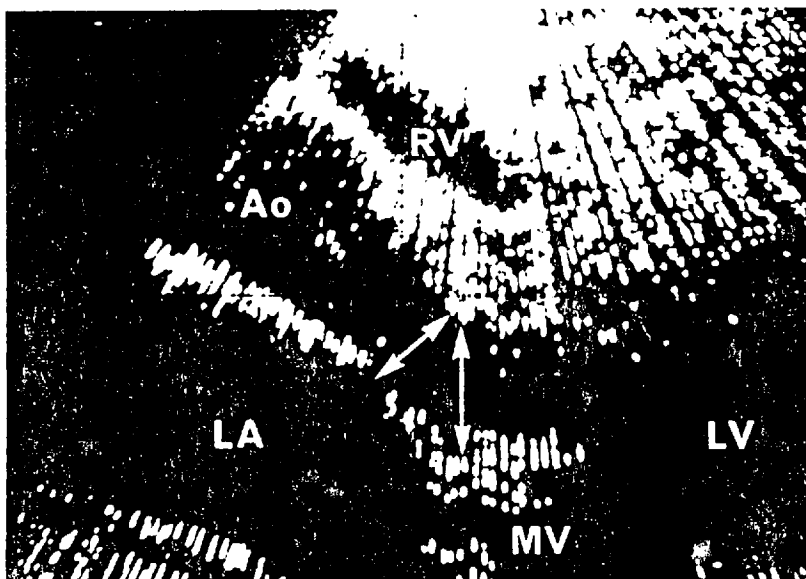


Figure 90.
Triggered B-scan
(TBS) of a patient
with hypertrophic
cardiomyopathy
and an upper septal
bulge. The two ar-
rows indicate out-
flow tract measure-
ments with TBS, the
vertical arrow the
beam direction in
M-scanning.

Another important message was that LVOT size is different when measured from a two-dimensional scan and from the corresponding M-scan. The vertical arrow indicates the level at which the M-scan measurement would be made, as generally agreed from the closed mitral valve position to the septum.⁵⁷ However, the actual size of the outflow tract can be measured more accurately on the two-dimensional scan (small arrow). In order to make such measurements one has to carry out several sweeps from different directions, and take the smallest possible dimension in the aorto-mitral transition zone. Fig. 91 demonstrates an interesting feature of a patient

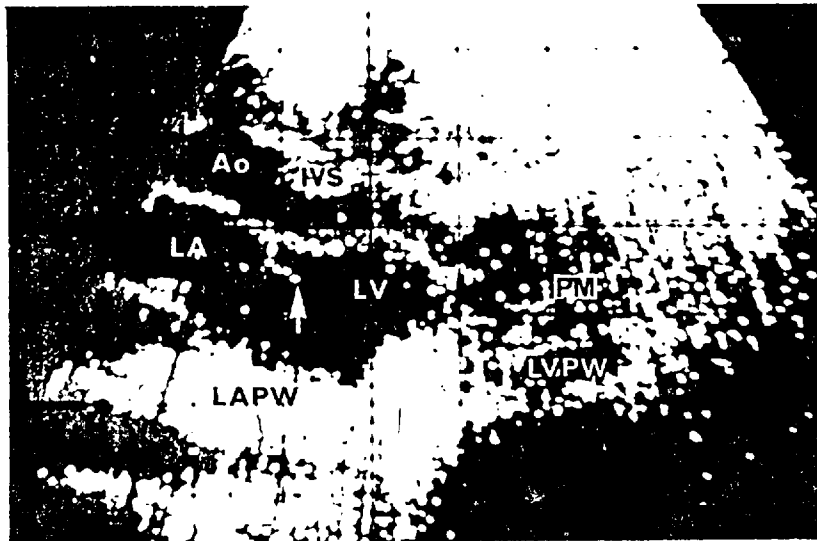


Figure 91. Triggered B-scan of a patient with hypertrophic cardiomyopathy. See text. (LAPW, LVPW=left atrial and ventricular posterior wall, PM=papillary muscles).

who shows an incomplete 'SAM' on the M-scan echogram as seen later in fig. 92. The B-scan, triggered in early systole, shows proximal chordae tendineae bulging forward into the left ventricular outflow tract, while the anterior leaflet itself (see arrow) is clearly in a more closed position. This seems to indicate that part of the chordae are moving anteriorly when the posterior mitral leaflet is moving posteriorly. This was taken as further support that 'SAM' was produced by the papillary muscles, and that one is able to show this feature in two-dimensions.

Fig. 92 shows a continuous line above the echoes of the left ventricular posterior wall, which was interpreted as thickened posterior chordae in the transition zone to the posterior papillary muscles. The obvious feature of this posterior chordal structure is that it follows exactly the motion of the left ventricular poste-

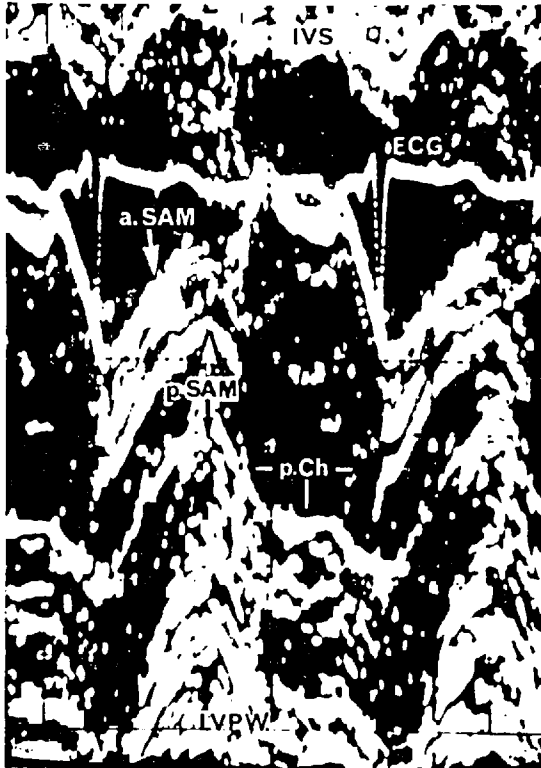
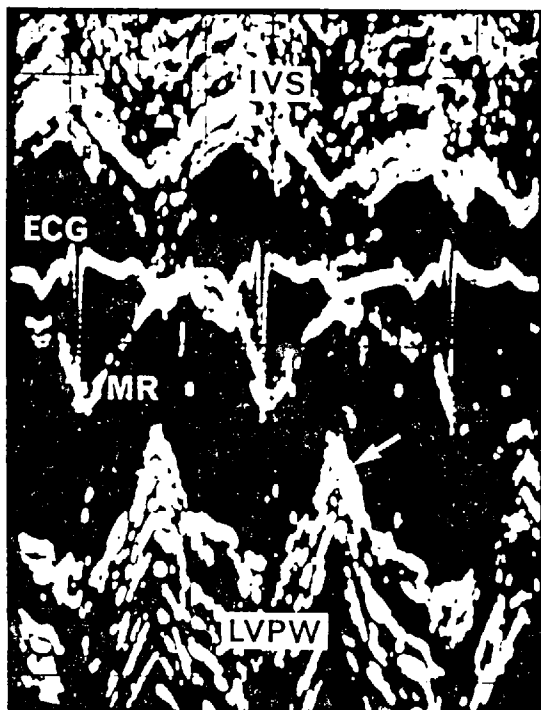


Figure 92. M-scan echocardiogram of a patient with hypertrophic cardiomyopathy, showing an incomplete 'SAM' and thickened posterior chordae (p.Ch) overlying the left ventricular posterior wall (LVPW). The 'SAM' complex consists of anterior and posterior structures (a., p.SAM). (IVS=interventricular septum, ECG=electrocardiogram).

rior wall and also the configuration of the 'SAM' structures. This was different when scanned from a different angle (see fig. 93). In this scan anterior and posterior chordal structures



are seen wider apart. The very bright posterior chordae (arrow) are shown here near the cardiac apex to lie closer to the left ventricular posterior wall and to follow the hyperkinetic systolic anterior motion of the posterior wall even more dramatically. This probably in-

Figure 93. M-scan of the patient in fig. 92 obtained from a different beam direction. The thickened posterior chordae (arrow) follow the left ventricular posterior wall (LVPW) very closely while the anterior chordae adopt the motion pattern of the mitral ring (MR).

dicates that anterior 'SAM' structures should not be correlated with the pattern of left ventricular posterior wall motion, since only the posterior chordae follow that pattern.

When looking at a post-operative scan of this patient, in whom a septal myectomy was carried out, one can clearly see (fig. 94) the thickened anterior mitral valve leaflet

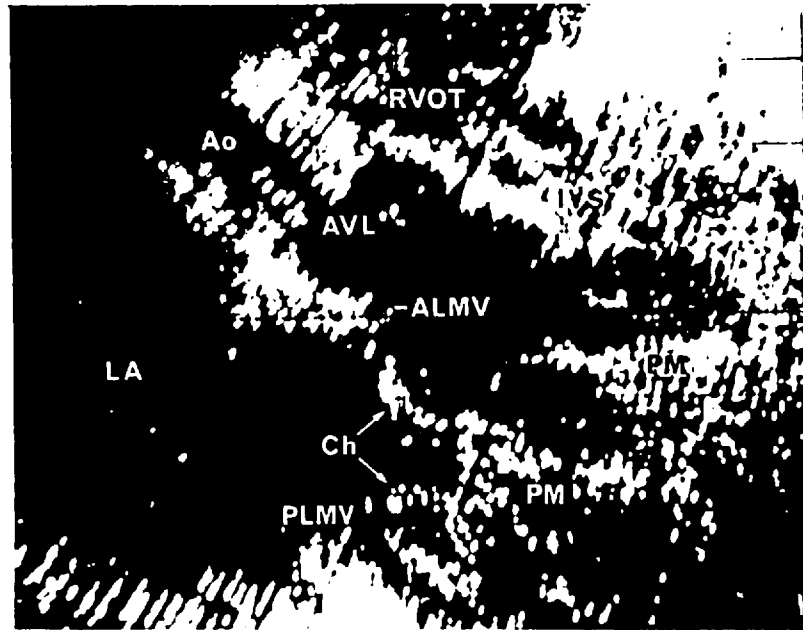


Figure 94. Triggered B-scan of the patient in figs. 92 and 93 after septal myectomy. The anterior and posterior mitral valve leaflets (ALMV, PLMV) are wide open while the chordae tendineae (Ch) are curved towards each other due to the posterior position of the papillary muscles (PM) in diastole. (Ao=aortic root, AVL=aortic valve leaflets, RVOT=right ventricular outflow tract, LA=left atrium).

wide open, when triggered at an early diastolic phase, and the chordae and posterior papillary muscle drawn back towards the left ventricular posterior wall. This creates an obvious angle between the mitral valve tip and the chordae, suggesting that the chordae are moving backward when the anterior mitral leaflet is moving anteriorly, and vice versa when comparing with fig. 91. This complied very well with the M-scan in fig. 92 and indicated already in 1973 that 'SAM' may be produced by chordae motion rather than by the mitral valve leaflets themselves. Early mention of this hypothesis was met with

disapproval and I therefore waited till November 1975, after real-time B-scan echocardiography had supported this view and helped to develop a new approach to the interpretation of the typical M-scan features in hypertrophic cardiomyopathy. This will be discussed in more detail in the next chapter.

G. CONCLUSIONS

Triggered B-scan echocardiography is a valuable adjunct to M-scanning because it offers an exact anatomical orientation in any pre-selected plane of the heart and at any pre-determined cardiac phase. It may always give additional echographic information when the diagnosis is based upon changes in structural relationships. The method may also be used for assessing functional parameters, but the time consuming procedure makes it unsuitable for a routine application in day to day assessment of cardiac patients. This method is clearly superseded by real-time B-scan echocardiography, although it may still be valuable in specific cases where use can be made of the particular advantage of collecting data from different positions and angles on the chestwall within a pre-determined scanning plane but at any desired phase of the cardiac cycle.

CHAPTER X

REAL-TIME B-SCAN ECHOCARDIOGRAPHY:
ITS INFLUENCE ON THE UNDERSTANDING OF
M-SCAN FEATURES AND SOME PATHOPHYSIOLOGICAL MECHANISMS
IN HYPERTROPHIC CARDIOMYOPATHY

In this chapter the experience with the linear real-time B-scanner, the Siemens 'Vidoson' is described.

The previous work with conventional and triggered B-scanning made it very easy to use this new equipment immediately for all kinds of diagnostic purposes.

My main interest, however, was geared towards hypertrophic cardiomyopathy, stimulated by first results with M-scanning and early findings with triggered B-scan echocardiography.

A. THE MECHANISM OF SYSTOLIC ANTERIOR MOTION ('SAM') IN HYPERTROPHIC CARDIOMYOPATHY: A COMPARISON OF ONE-DIMENSIONAL WITH TWO-DIMENSIONAL ECHOCARDIOGRAPHY

The systolic anterior motion of mitral valve structures in the M-scan echocardiogram, as initially demonstrated in 1968 and 1969⁵⁸⁻⁶⁰ has been considered diagnostic of hypertrophic cardiomyopathy with left ventricular outflow tract (LVOT) obstruction⁶¹⁻⁶⁴, and also to be the cause of mitral regurgitation frequently found in this condition⁵⁹⁻⁶². 'SAM' of the anterior leaflet of the mitral valve in association with mitral regurgitation had been previously demonstrated by left ventricular angiography^{65,66,67}, and it was therefore natural to assume that the echocardiographic 'SAM' would have a similar mechanism and significance.^{63,64,68,69}

The demonstration of a close relationship between the form of 'SAM' and the severity of haemodynamic LVOT obstruction⁶² seemed to further confirm this view. There are, however, several features of the echographic 'SAM' which make such an explanation unsatisfactory. If the linear echoes of the anterior and posterior margins of the 'SAM' structures are reflections of the mitral valve leaflets, it is difficult to understand firstly how the posterior leaflet can be stretched anteriorly beyond its normal position of closure; and secondly how spotty echoes, typical of reflections off myocardial tissue are frequently found within 'SAM' between the two linear margins. Furthermore 'SAM' has been described in conditions

other than hypertrophic cardiomyopathy.^{64,69,70,71}

The first part of this chapter will deal with the M-scan echographic findings in hypertrophic cardiomyopathy and show early results which aroused doubts about the validity of the M-scan echographic diagnosis and the implied mechanisms for mitral regurgitation and left ventricular outflow tract obstruction in this disease. These doubts were supported by the triggered B-scan findings as described earlier, and the second part of this chapter will deal with the real-time B-scan findings, with a technique which allowed observation of the mitral valve leaflets during the entire cardiac cycle, which had not previously been achieved with any other non-invasive or invasive method of investigation.

1. M-scan findings

Fig. 95 shows the M-scan echographic changes of the

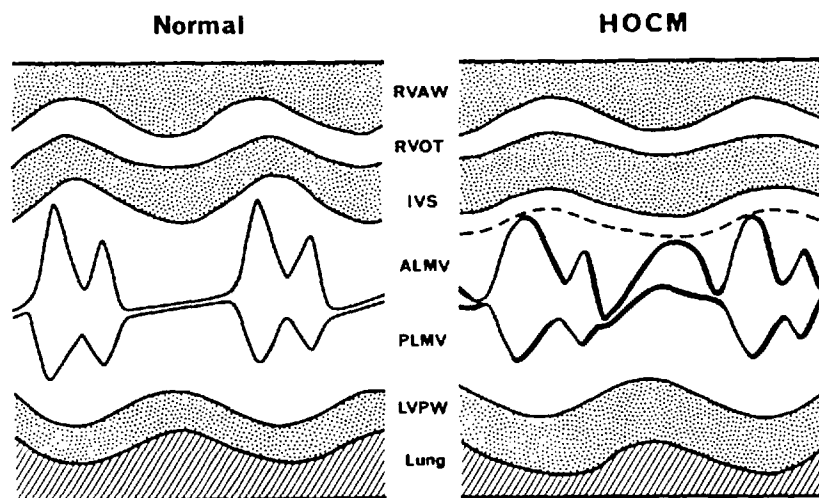


Figure 95. Diagrammatical comparison of the normal mitral echogram with that in hypertrophic cardiomyopathy. (RVAW=right ventricular anterior wall, RVOT=right ventricular outflow tract, IVS=interventricular septum, ALMV, PLMV=anterior and posterior leaflets of the mitral valve, LVPW=left ventricular posterior wall). See text.

mitral valve in patients with hypertrophic cardiomyopathy, as compared to normals. In this disease the right ventricular

outflow tract often almost completely disappears and is well seen only in associated right ventricular volume overload. Interventricular septum and left ventricular posterior wall are thickened, and when the ratio of septal to left ventricular wall thickness is 1.3, then ventricular hypertrophy in these patients has been described as asymmetrical hypertrophy or ASH⁵⁷ and otherwise as concentric left ventricular hypertrophy. The anterior leaflet of the mitral valve often touches the interventricular septum in early diastole, and the left ventricular endocardium of the septum often shows a bright echo in this region. The diastolic closure rate is decreased and the echoes from the mitral leaflets appear thickened. In systole, instead of a normal straight anterior motion of the closed mitral leaflets, produced by the descent of the atrio-ventricular ring plane towards the transducer (left panel), structures are moving anteriorly and often touching the interventricular septum. Since these anteriorly moving structures, whose brightness often exceeds that of the M-shape of the mitral valve echogram, are in direct continuity with the diastolic M-shape structures, it was understandable that 'SAM' was interpreted as re-opening of the mitral valve itself. If 'SAM' indeed represented mitral valve leaflet tips, then all patients with complete or incomplete 'SAM'⁷² should have mitral regurgitation. We observed earlier, however, that several of our patients with a complete or incomplete 'SAM' during M-scan echocardiography did not show mitral regurgitation during left ventricular angiography.

A second finding was that the amplitude of 'SAM' could be altered at will by changing the direction of the single ultrasonic beam. I therefore concentrated on the 'SAM' structures during the M-scan echographic examination and found that the 'SAM' echo did not return to the D-point⁷³ of the echogram and even seemed to move through the area otherwise occupied by the mitral valve leaflet motion.

The following figures are all from one patient with non-obstructive hypertrophic cardiomyopathy associated with mild mitral regurgitation. In this patient I succeeded in showing all the puzzling M-scan echographic features of this disease

at a time when only Polaroid recordings were available to us.

Fig. 96 shows the echoes from the anterior leaflet of the

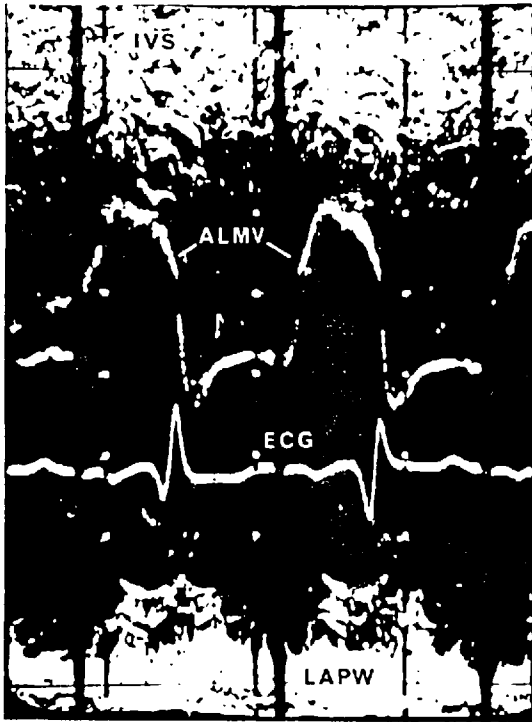


Figure 96. M-scan echogram of the anterior leaflet of the mitral valve (ALMV) of a patient with hypertrophic cardiomyopathy, showing a very mild systolic anterior motion (SAM). For orientation see fig. 95.



Figure 97. M-scan echogram of the same patient as in fig. 96, showing a more prominent 'SAM' complex when pointing the transducer more towards the apex. (See fig. 95 for orientation).

mitral valve between the interventricular septum anteriorly and the left ventricular posterior wall posteriorly. The diastolic closure rate is considerably reduced and the atrial kick or A-wave is hardly seen. The systolic mitral valve echo shows a small 'SAM'. Directing the beam more apically we can see in fig. 97 that the amplitude of 'SAM' is larger and appears as a complex of several linear structures.

Directing the beam even further towards the apex, as shown in fig. 98, 'SAM' appears to touch the septum in systole, and the complex shows two main linear echoes which appear considerably thicker than in the previous examples. Some spotty echoes within 'SAM' look like soft tissue reflections. This, however,

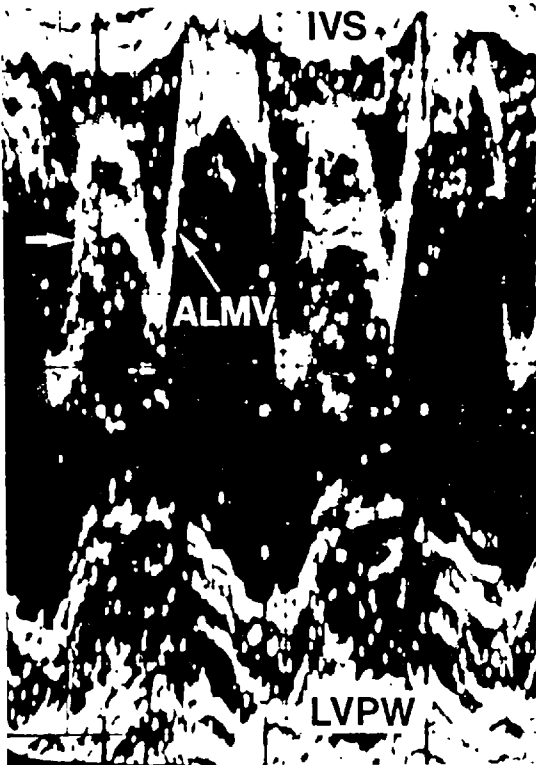


Figure 98. M-scan echogram of the same patient as in figs. 96 and 97 now exhibiting a complete 'SAM', touching the septum, when the beam is directed further to the apex.

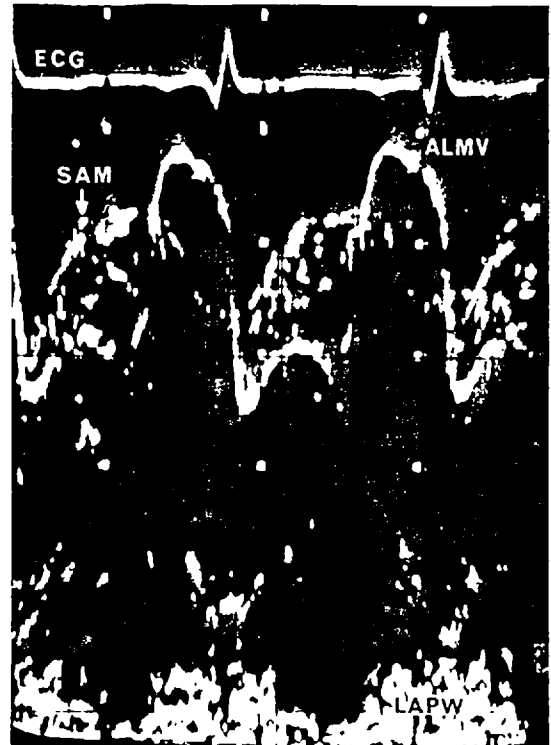


Figure 99. M-scan of the patient in fig. 98, showing a 'pseudo-SAM' pattern, which was found to be chordae tendineae as well. For orientation see fig. 96 and text.

cannot be differentiated in this example from spotty echoes which occur with turbulence. In this and all the other examples 'SAM' returns to the D-point before the mitral valve opens again in early diastole. Scanning at a different level in the same patient, as in fig. 99, we see a 'SAM' complex which does not return to the D-point and which seems to move through the mitral valve echo structures to be continuous with the 'SAM' of the next cardiac cycle (see arrow). Further more the spotty echoes within 'SAM' seem to be localised only in this area and not elsewhere on the M-scan.

Fig. 100 was obtained when the beam was directed more apically to visualise the posterior leaflet of the mitral valve as well. In this view the hyperdynamic contraction pattern of the left ventricular posterior wall is seen. The left ventricular endocardium of the septum is very bright and so are the 'SAM' structures as compared to the remnants of the diastolic



Figure 100. M-scan of the patient in figs. 96-99, with anterior and posterior 'SAM' structures. For orientation see fig. 96.

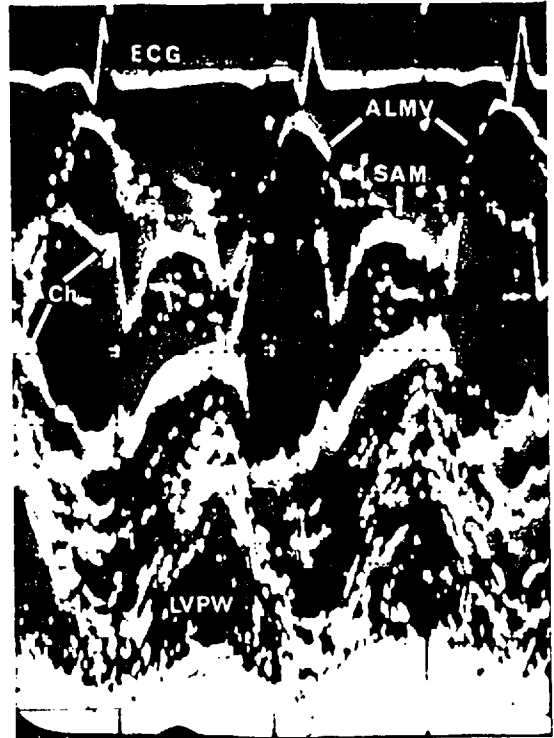


Figure 101. M-scan of the patient in figs. 96-100 showing with different beam direction a continuous structure, moving through the diastolic anterior leaflet motion pattern and forming the 'SAM' anteriorly. For orientation see fig. 96.

features of the mitral valve motion. The rest of the septal myocardium is suppressed by the gain settings. The second anterior 'SAM' configuration appears to originate already in the diastolic configuration of the mitral valve motion. This, however, is not obvious enough to be conclusive. I therefore concentrated on the 'SAM' structures during the entire cardiac cycle and the most complete example I could obtain is seen in fig. 101. One can see three diastolic complexes of mitral valve motion, which are only faint and interrupted in the region of the anterior mitral leaflet. The anterior and particularly the posterior 'SAM' structures are markedly thickened. The posterior 'SAM' is in continuity with a nearly equally thickened diastolic structure which follows the posterior leaflet motion. At the end of systole anterior as well as

posterior mitral valve echoes appear to start from the posterior 'SAM' structure to open in early diastole. The posterior 'SAM' follows in shape and time the hyperactive motion of the left ventricular posterior wall, particularly in systole. The anterior 'SAM' is not synchronous with the posterior 'SAM' or left ventricular posterior wall motion, and in continuity with echoes which can clearly be seen within the anterior mitral valve leaflet configuration of diastole. From this it could only be concluded that most of the time, when one tries to image a good 'SAM' and also a good pattern of diastolic mitral valve motion, the tips of the mitral leaflets may be within the ultrasonic beam during diastole while in systole chordae tendineae may move into the beam. This change cannot be spotted on the M-scan except perhaps by changes in thickness. In this example I succeeded for the first time to concentrate on the structure forming the 'SAM' and following it throughout the cardiac cycle without forming a continuity or fusing with the mitral leaflet motion pattern. Thus it appears here that the typical pattern from the mitral leaflet flashes into the beam only at times in addition to the chordal structures which are within the ultrasonic beam during the entire cardiac cycle.

In order to show how the amplitude of SAM can be changed

by altering the beam direction, a rapid sweep was carried out from a more apical direction towards the base of the heart within one cardiac cycle. This could be visualised even on Polaroid recording, as shown in fig. 102. The initial part of systole shows multiple incomplete 'SAM' struc-

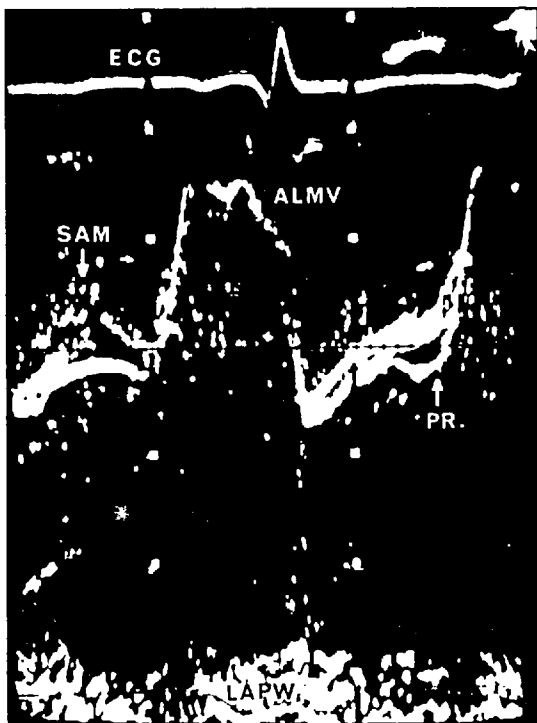


Figure 102. M-scan of the patient in figs. 96-101, showing with different beam direction a late systolic posterior mitral valve prolapse (PR) and a SAM in the previous systolic phase of the cardiac cycle. (LAPW=left atrial posterior wall, ALMV=anterior leaflet of the mitral valve).

tures the upper and fainter ones of which move into the diastolic configuration of the anterior leaflet motion. When pointing the beam more towards the mitral valve tip area, the second systolic configuration of mitral valve motion shows only a slightly anteriorly convex pattern and the posterior echo exhibits a late systolic posterior motion, typical of a posterior mitral valve prolapse. This particular configuration is often seen in mid-systolic click and late systolic murmur syndrome.⁷⁴ I therefore concluded from these findings that the main mechanism of mitral regurgitation in hypertrophic cardiomyopathy may be mitral valve prolapse. This was subsequently discussed,⁷⁵ after having seen many more indications from the M-scan echocardiograms of patients with hypertrophic cardiomyopathy.

Since one could produce incomplete, complete, and pseudo-'SAM' in the same patients just by changing the angle of incidence of the ultrasonic beam, it becomes quite clear that there may be only one mechanism of systolic anterior motion of the mitral valve echo structures, so that a differentiation between 'SAM' and pseudo-'SAM' seems irrelevant.

In view of the conflicting observations with M- and triggered B-scan echocardiography I embarked on a real-time B-scan study, which was performed in addition to routine M-scan investigations in patients admitted for cardiac catheterisation and angiography for diagnostic purposes.

2. Comparison of M- and real-time B-scan findings in hypertrophic cardiomyopathy

a. Methods and material

Fifteen patients with hypertrophic cardiomyopathy, 11 men and 4 women, with a mean age of 35 years, ranging from 11 to 62 years, have been studied by RTBS. This was performed with a mechanical B-scanner, the Siemens 'Vidoson', described on p.20. The scanning technique with this method is described on p.51. In all patients the standard longitudinal cross-sectional plane was recorded and in 11 patients the applicator

was rotated perpendicularly to the longitudinal cardiac axis to give a transverse cross-section at various levels of the heart. For precise analysis of these recordings the frames have been replayed as combined images with the electrocardiogram at normal speed, in slow motion or as single frames, and then photographed for the figures. All patients were also studied by M-scan echocardiography in the normal manner,⁷⁶ using a 2.5 MHz transducer and an ekoline 20 interphased with a Cambridge strip-chart recorder, as described on p. 19. A sweep from apex to base was carried out by pointing the transducer from the aortic root via the mitral valve apparatus towards the apex of the heart.

Routine diagnostic cardiac catheterisation was performed on all patients and included left ventriculography in the standard right anterior-oblique position. Pressure measurements were obtained either by three simultaneously inserted catheters in the left ventricular cavity, in the outflow chamber, and in the aorta, or by withdrawal from the left ventricle into the aorta. In patients with no resting gradients amyl nitrite was given by inhalation in order to provoke a gradient, and intravenous phenylephrine was used to abolish it. The results were classified as obstructive hypertrophic cardiomyopathy⁷⁷ when a resting gradient was recorded, as labile obstruction when a gradient could only be provoked in post-extrasystolic beats or by amyl nitrite, and as non-obstructive when no gradient was found either at rest or on provocation.

b. Results

The angiographic, M-scan, and real-time B-scan echographic results of this study are summarised in table 6.

- Haemodynamics and angiography:

Resting gradients between the left ventricular cavity and left ventricular outflow tract below the aortic valve were recorded in eight patients. In five other patients, who had no obstruction during sinus rhythm at rest, a gradient was recorded during post-ectopic beats or could be provoked with

patients No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
age	62	11	32	19	60	40	31	19	54	34	18	50	11	30	55
sex	F	M	F	M	M	M	M	M	F	M	M	M	M	F	M
Catheter and Angio obstruction - LVOT	-	-	1	1	1	1	1	+	+	+	+	+	+	+	+
obstruction - RVOT	+	-	-	-	-	-	-	+	-	-	-	+	-	-	-
mitral regurgitation	-	+	-	-	++	+	+	-	++	+	+	+	++	++	++
M-Scan															
SAM anterior	ic	ic	ic	ic	ic	c	c	c	ic	ic	c	c	c	c	c
SAM posterior	+	+	(+)	Ø	+	(+)	+	+	+	+	+	+	Ø	+	+
SAM prolonged apposition to IVS	-	-	-	-	-	-	+	+	-	-	+	-	+	+	-
SAM - spotty echoes	-	-	-	-	-	+	+	+	-	-	-	+	+	-	-
enhanced SAM echoes	-	+	-	-	-	+	+	+	+	-	-	+	+	-	-
LVPW - EDD (cm)	2.0	1.0	1.2	1.0	1.0	1.2	1.3	1.1	1.3	2.3	1.2	1.6	1.2	1.3	1.4
IVS - EDD (cm)	1.5	1.5	1.7	1.9	2.5	2.1	2.3	1.9	1.8	2.8	2.0	3.0	2.0	2.4	2.4
Real-time B-Scan															
Standard Longitudinal X-Section:															
IVS bulge - localised hypertrophy (l) and generalised hypertrophy (g)	l	l	l	l	g	l	l	l	g	g	g	l	l	l	l
IVS bulge - thickened endocardium with subendoc. damping	+	+	+	+	+	+	+	++	(+)	+	(+)	+	+	+	+
ALMV thickening	+	+	+	+	+	++	++	+	+	-	+	+	+	(+)	+
PLMV thickening	-	+	-	+	+	+	-	-	(+)	Ø	(+)	-	+	+	-
prominent papillary muscles	+	+	+	+	-	+	+	+	++	+	+	Ø	+	+	-
prominent chordae tendineae	+	+	+	+	-	+	+	+	+	+	+	(+)	+	+	+
opposed chordae motion	-	+	+	+	-	+	+	+	-	(+)	++	-	++	(+)	-
LVPW brightness enhanced	+	+	+	+	+	+	+	-	+	+	+	+	+	+	+
Latitudinal X-Section:															
IVS bulge (RV)	-	-	+	Ø	-	-	Ø	-	Ø	-	-	-	+	+	Ø
IVS bulge (LV) - localised (l) and generalised (g) thickening	l	g	l	Ø	g	l	Ø	l	Ø	l	l	l	l	l	Ø

Table 6. Summary of data obtained from 15 patients with hypertrophic cardiomyopathy. Abbreviations of angiocardiology: -=non-obstructive, 1=labile and +=fixed left ventricular outflow tract obstruction; obstruction in the right ventricular outflow tract (RVOT): -=absent, +=present; mitral regurgitation (MR) is classified in -=absent, +=minimal and ++=moderate MR.

M-scan echocardiography: SAM=systolic anterior motion of mitral valve structures; LVPW-EDD=left ventricular posterior wall thickness at end-diastole (cm); IVS-EDD=interventricular septal thickness at end-diastole (cm); ic=incomplete, c=complete.

Real-time B-scan echocardiography: ALMV and PLMV=anterior and posterior leaflets of the mitral valve; (+)=less prominent, +=prominent, ++=marked features observed, -=absent, Ø=technically deficient.

By permission of Clinical Cardiology.⁷⁸

amyl nitrite and then abolished with phenylephrine. In the remaining two patients no gradient was found either at rest or following provocation. Mitral regurgitation was observed on the left ventriculogram in eleven patients and classified as mild in six and moderate in five patients. There was no significant association with the type of left ventricular outflow tract obstruction since mitral regurgitation was observed only in seven out of eight patients with obstructive hypertrophic cardiomyopathy, in three out of five patients with labile obstruction and in one out of two patients with non-obstructive hypertrophic cardiomyopathy. In three patients a gradient in the right ventricular outflow tract was recorded.

- M-scan echocardiography:

A typical M-scan recorded in hypertrophic cardiomyopathy is seen in fig. 103. The interventricular septum, measured at

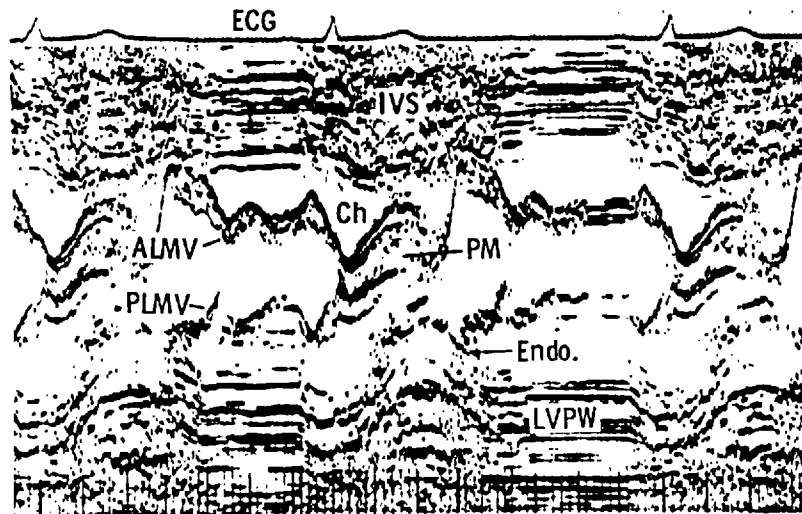


Figure 103. M-scan of a patient with hypertrophic cardiomyopathy. The linear borders of the 'SAM' configuration are believed to represent chordae and the spotty echoes inside papillary muscle reflections. (Endo.=endocardium, other labels as in previous figs.)

By permission of Clinical Cardiology.⁷⁸

the peak of the R-wave on the simultaneously recorded electrocardiogram was thickened in all patients (mean=2.1 cm $\pm$ 0.44

standard deviation, ranging from 1.5 - 3 cm). The left ventricular posterior wall, also measured at the peak of the R-wave of the electrocardiogram was abnormal only in twelve patients (mean value=1.34 cm $\pm$ 0.37 standard deviation, ranging from 1.0 - 2.3 cm). There was no significant association between 'SAM' and left ventricular posterior wall thickness (point biserial correlation coefficient=-0.15, $p < 0.05$). Using Fisher's Exact Test no highly significant association was found between 'SAM' and left ventricular outflow tract obstruction ($p < 0.05$), and there was also no highly significant association between left ventricular posterior wall thickness and the type of left ventricular outflow tract obstruction (Spearman's Rank Correlation Coefficient= 0.34, $p < 0.05$). The systolic anterior motion of the mitral valve apparatus was classified as either complete or incomplete according to the amplitude and presence or absence of contact with the interventricular septal echoes in systole.⁷² 'SAM' of the anterior mitral valve leaflet structures was present in all patients, in eight being complete and in the other seven incomplete. A prolonged proximity to the interventricular septum was seen in five members of the complete 'SAM'-group. The two patients in this series without any obstruction (patients one and two) had an incomplete 'SAM' (see table 6). Of the five patients in the group with labile obstruction (patients 3-7) two had a complete and three an incomplete 'SAM'. A prolonged approximation to the septum during systole of the echocardiographic 'SAM' (patients 7,8,11,13 and 14) did not adequately predict the haemodynamic findings. Of the eight patients with fixed left ventricular outflow tract obstruction prolonged 'SAM' was recorded in four and absent in the other four patients. A 'SAM' of the posterior mitral valve apparatus was observed in five patients, while in seven patients 'SAM' appeared to be more prominent than the echoes of the mitral valve during diastole.

- Real-time B-scan echocardiography:

Normal heart: a two-dimensional real-time B-scan in the standard longitudinal cross-section (RAO-projection of angiography)

is shown in fig. 104. The unobstructed left ventricular out-

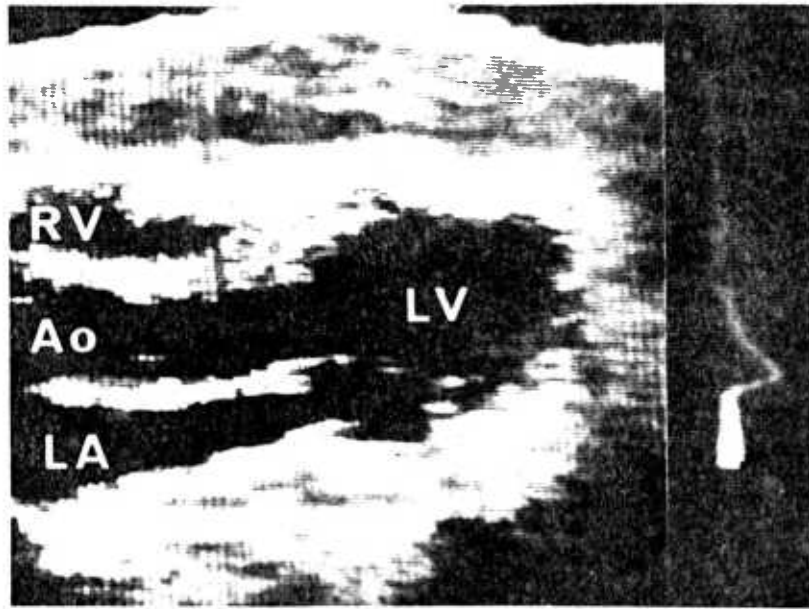


Figure 104. Real-time B-scan in the standard longitudinal cross-section of a normal individual in systole. (RV, LV=right and left ventricles, Ao=aortic root, LA=left atrium).

flow tract is clearly visible. Normal motion of anterior mitral leaflet is characterised by a whip-like double upward motion resulting in the typical M-shape configuration in M-scan echocardiography. In this longitudinal plane, as in single dimensional scanning the most antero-lateral part of the right ventricular outflow tract is seen. Chordae tendineae are normally not or are only faintly visible within the left ventricle.

Hypertrophic cardiomyopathy: The different appearance of the standard longitudinal cross-section through the heart of a patient with hypertrophic cardiomyopathy can be readily appreciated from fig. 105. The overall increase in myocardial mass is apparent on this end-diastolic frame (see P-wave of the simultaneously recorded electrocardiogram). The left ventricular cavity appears small, and the aortic root and mitral valve leaflets appear thickened. There is an abrupt transition from the anterior aortic root into the immensely thickened inter-

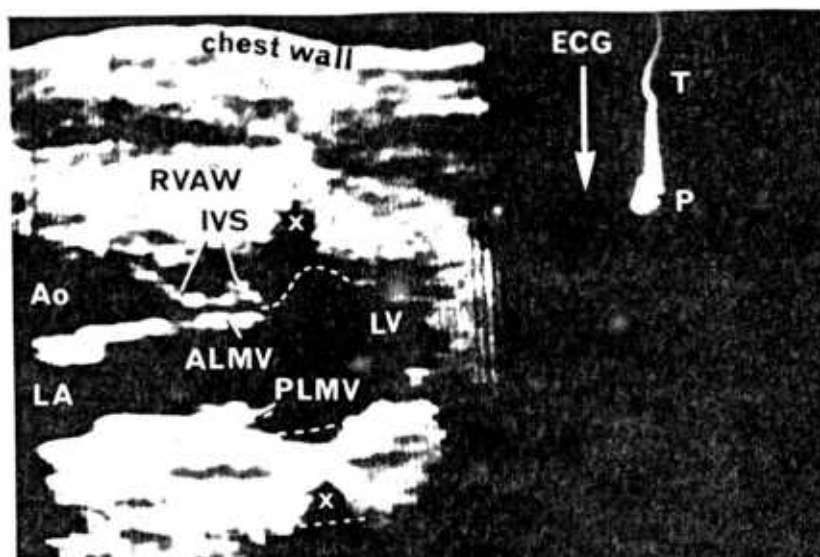


Figure 105. Real-time B-scan of a patient with hypertrophic cardiomyopathy, showing an upper septal bulge. (orientation: see fig. 104; RVAW=right ventricular anterior wall, ALMV and PLMV=anterior and posterior leaflets of the mitral valve).
By permission of Clinical Cardiology.⁷⁸

ventricular septum which bulges prominently into the left ventricular outflow tract so that the thickened anterior mitral leaflet touches the septum when open during diastole. The thickened endocardial surface of the interventricular septum is well delineated due both to thickening and to relative damping of the adjacent myocardium.⁷⁸⁻⁸¹ The echo free space (x) represents shadows produced by overlying ribs and the interrupted line indicates where the structures continued when the scanning plane was changed to avoid the ribs in this area. The left atrium is of normal shape and of normal size compared with the left ventricular cavity. The whip-like motion of the anterior mitral leaflet in hypertrophic cardiomyopathy is often not as prominent as in the normal and the effect of atrial contraction may be absent. These changes are not specific for hypertrophic cardiomyopathy, and we have observed them frequently in conditions with a low cardiac output.

A typical transverse cross-section through the heart in a patient with hypertrophic cardiomyopathy is shown in systole and diastole in fig. 106, as observed from the cardiac apex. The left ventricle is seen on the right and the half-moon shape

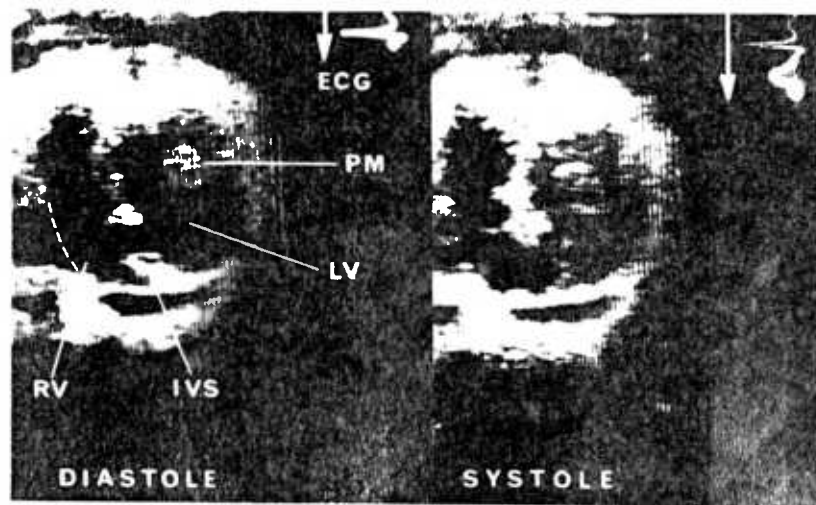


Figure 106. Transverse cross-sections of a patient with hypertrophic cardiomyopathy, in end-diastole (left) and systole (right). The anterior papillary muscle (PM) within the left ventricle (LV) moves from the antero-lateral wall towards the septum. By permission of Clinical Cardiology.⁷⁸

of the right ventricle on the left (compare fig. 46, n.63). The cross-section is taken below the septal bulge in order to visualise the papillary muscles which are forcibly moved towards the IVS during systole. In normals papillary muscles are not seen at this level. For this transverse cross-section the B-scan applicator was slightly tilted superiorly in its long axis at an angle of about 10° - 15° from the antero-posterior position, thus pointing towards the right shoulder of the patient. This can be seen from the two echo free spaces within the posterior wall of the heart, the longer one on the right representing the coronary sinus and the smaller one on the left representing part of the inferior vena cava.

Prominent papillary muscles were observed in twelve of fourteen patients with hypertrophic cardiomyopathy. The septal thickening was seen as a localised bulge in the upper third of the interventricular septum in eleven patients. The left ventricular endocardial surface of the septum was prominently outlined and emphasised by subendocardial damping of the adjacent myocardium in all cases. In the left ventricular posterior wall unusual brightness was observed in fourteen patients. The anterior mitral valve leaflet was thickened in fourteen

and the posterior leaflet in eight patients. Prominent chordae were apparent in fourteen patients, and in thirteen of those patients the papillary muscles were also seen. The chordae tendineae were observed to move during both phases of the cardiac cycle in a direction opposite to the movement of the anterior leaflet in ten of the fifteen patients. Transverse cross-sections were recorded in eleven patients in whom two had a generalised bulge of the septum into the left ventricle and the remaining nine a pronounced localised bulge. In three patients the interventricular septum was seen also to bulge into the right ventricular cavity. These were not the same three patients who were noted to have a right ventricular outflow tract gradient at cardiac catheterisation.

When comparing the prominent papillary muscles with the form analysis of 'SAM' in M-scanning, no significant association was found using Fisher's Exact Test ($p < 0.05$).

C. DISCUSSION

Since the first description of the systolic anterior motion on M-scan in hypertrophic cardiomyopathy^{58,59} it has been assumed, until recently, that 'SAM' represents echoes from the mitral valve leaflets.^{57,70,82} Such mitral valve motion had initially been demonstrated angiographically,⁶³⁻⁶⁵ and appeared to compare well with earlier direct anatomical observations during operation.⁸³⁻⁸⁵ The angiographic systolic opening of the mitral valve in hypertrophic cardiomyopathy has recently been reconfirmed,^{62-64,70,86} but it is notable that it is infrequently seen, even though the echocardiographic 'SAM' structures are easily detected and often have an amplitude equal to the diastolic opening of the mitral valve. Both left ventricular outflow tract obstruction^{61,82,87,88} and mitral regurgitation in hypertrophic cardiomyopathy have been attributed to the systolic anterior motion of the mitral leaflets.⁶⁵⁻⁶⁹ However, the predictions of a left ventricular outflow tract gradient by form analysis of 'SAM'

structures in M-scanning,⁶² have not been confirmed in this study. Furthermore, the absence of any visible mitral regurgitation on the left ventricular angiograms in four of our fifteen patients, in all of whom there was an echographic 'SAM', argues against 'SAM' resulting from echoes of the mitral valve leaflets. If 'SAM' were indeed due to systolic mitral valve re-opening, then mitral regurgitation should be a consistent finding in all cases showing 'SAM' in M-scan echocardiography. This, however, has not been our experience. The mechanism of the mitral regurgitation in the other ten patients in this series is uncertain since the leaflets appeared on real-time B-scanning to be normally closed throughout systole or rarely slightly separated at the mitral valve tips. This could either be explained by inappropriate position while scanning through lateral parts of the closed mitral valve leaflets, or by undue traction of the tips of the leaflets. Mitral regurgitation in hypertrophic cardiomyopathy has been attributed to systolic re-opening of the mitral valve,^{65,89} failure of apposition of the valve leaflets throughout systole⁶⁶⁻⁶⁸ or posterior mitral valve prolapse.⁷⁵ The poor correlation of the echographic 'SAM' with the type of left ventricular outflow tract obstruction and mitral regurgitation in hypertrophic cardiomyopathy is some indirect evidence that 'SAM' might not be a reflection of the mitral valve leaflets themselves. Moreover, 'SAM' has been recorded on echocardiograms in other conditions not necessarily associated with outflow tract obstruction, such as apical left ventricular aneurism,⁷⁰ systemic hypertension,^{71,90} aortic valve disease,^{64,90} coronary artery disease,⁹¹ mitral and aortic regurgitation, mitral valve prolapse and cleft mitral valve,⁷² in ventricular septal defect, hyperkinetic heart syndrome, athletes, normal subjects after exercise, post-ectopic beats, bradycardia and any condition resulting in a vigorous anterior motion of the left ventricular posterior wall.⁹⁰ Indirect evidence that the subvalvular apparatus of the mitral valve is mainly responsible for 'SAM', may be available from the M-scan echocardiographic sweep from the aortic root to the cardiac apex. Only a very small 'SAM' may be visualised at a level where the anterior mitral leaflet

is first seen, but by pointing the transducer further towards the apex the amplitude of 'SAM' may be considerably increased. If such a sweep is carried out slowly enough one can see initially that the 'SAM' structures consist of single lines, which are filled with spotty echoes when the beam approaches the apex. These spotty echoes are typical of myocardial tissue and suggest scanning through papillary muscles. The real-time B-scan findings of this investigation may explain some of the puzzling features of M-scan echocardiography in hypertrophic cardiomyopathy. The longitudinal cross-section of the mitral cusps during the entire cardiac cycle showed that they closed normally and did not re-open during systole. Linear structures, however, apical to the tips of the mitral valve leaflets were repeatedly observed moving in opposite direction to the anterior mitral leaflet. This can be seen in fig. 107 where maxi-

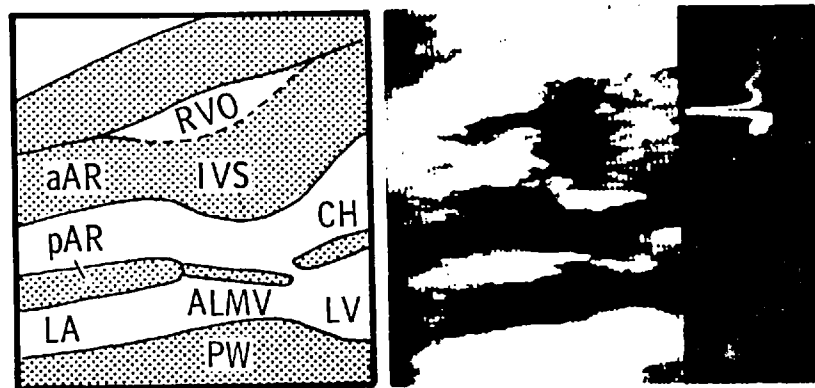


Figure 107. Section of a real-time B-scan and corresponding diagram, with low gain settings stressing the prominent septal endocardium and chordal structures distal to the anterior mitral valve leaflet (ALMV). (aAR, pAR=anterior and posterior aortic roots, RVO=right ventricular outflow, IVS=interventricular septum, PW=posterior wall).⁷⁸
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mal decrease in gain settings suppressed myocardial structures, but did not obliterate the strong reflections from the endocardial border and the echoes apical to the mitral valve leaflets. These structures are best interpreted as thickened chordae tendineae. These observations led initially to the following theory, as illustrated in fig. 108. The explanation of

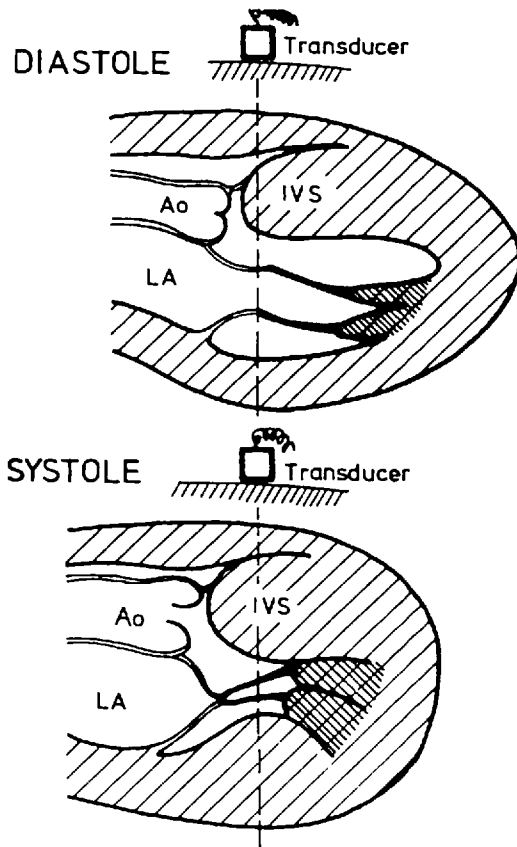


Figure 108. Diagrammatic representation of the M-scan beam direction through a heart with hypertrophic cardiomyopathy in diastole and systole. In the lower panel the mitral valve has left the beam to close and the anteriorly displaced chordae are captured in systole. (For orientation see previous figs.).

By permission of Clinical Cardiology.⁷⁸

this theory is more readily appreciated if the single ultrasonic beam is regarded as being static throughout the cardiac cycle. This is in accordance with earlier experience in M-scanning, that the transducer is often steadily held in a particular position where both mitral valve leaflets and maximal 'SAM' structures could be seen best. In this figure the ante-

rior aortic root is in continuity with the immensely thickened interventricular septum, and the posterior aortic root with the opened anterior mitral leaflet. Both mitral leaflets are in continuity with the thickened papillary muscles via thickened chordae tendineae. The tips of the widely opened mitral valve leaflets are placed within the fixed single ultrasonic beam in diastole. The structural changes in systole are illustrated in the lower panel of this figure. The initial hypothesis was that the thickened papillary muscles are squeezed together in systole and displaced towards the interventricular septum by the thickened and rigid left ventricular posterior wall (LVPW), with the chordae tendineae following this anterior motion. At the same time the tips of the mitral leaflets leave the fixed sound beam to close when the left ventricular pressure builds up. The structures remaining within the ultrasonic beam, thus recorded as 'SAM' in M-scanning, are probably the anteriorly moving chordae tendineae⁹¹, since M-scan echocardiography obviously cannot differentiate between the tips of the mitral valve leaflets and thickened chordae. With a sufficient

shortening of the left ventricle along the longitudinal axis, or a transducer position nearer to the cardiac apex, even parts of the papillary muscles or the entire hypertrophied papillary muscles may traverse the ultrasonic beam in systole, thus producing either spotty and/or multiple massive echoes within 'SAM' (see fig. 103). This would contrast with the recently offered suggestion that decreased longitudinal shortening of the left ventricle in systole may result in abnormal traction of the mitral valve leaflets with consequent systolic re-opening.⁸⁶

To gain evidence of the assumed systolic motion of the papillary muscles, transverse cross-sections were performed. In normal antero-posterior latitudinal cross-sections the right ventricle lies slightly in front of the left ventricle (10 o'clock position) and can rotate clockwise in right ventricular overload up to complete 12 o'clock position and anticlockwise in hypertrophic cardiomyopathy and other forms of left ventricular hypertrophy (fig. 106). The interventricular septum is seen between the ventricles and shows thickening in systole (right panel of fig. 106) and motion towards the left ventricular posterior wall, which contracts as well and moves simultaneously towards the interventricular septum. The anterior papillary muscle, normally lying antero-laterally, changes its normal systolic posterior-medial and superior direction of motion in marked left ventricular hypertrophy, with the anticlockwise rotation of the heart, and moves into a nearly true antero-posterior and superior axis towards the septum. This rotational change of motion explains why in single beam echocardiography this anterior motion (towards the transducer) with a maximal amplitude of 'SAM' is best seen when directing the single beam from the 3rd or 4th intercostal space near the sternum left laterally and sometimes even slightly inferiorly towards the cardiac apex.

The findings in the latitudinal cross-sections of our patients appeared to be the final link of the theory, which was subsequently reported to the British Cardiac Society in November 1975⁹¹. This presentation was to our knowledge the first publication that 'SAM' structures in hypertrophic cardiomyo-

pathy may be produced by a reflection off chordae tendineae and/or papillary muscles when traversing the fixed single ultrasonic beam in systole. It was suggested at that meeting that chordae tendineae might be arranged in a loose or slackened manner in front of the papillary muscles, thus being drawn into the outflow tract by aortic blood flow (Venturi effect) and visualised as 'SAM' in M-scan echocardiography. This interpretation in a study of four cases has subsequently been published⁹³ and suggests that the spotty echoes often recorded within 'SAM' indicate that the papillary muscles must become interposed between chordae tendineae. This could only occur if there was slackening of the chordae, a most unlikely event in a high pressure left ventricle, especially in circumstances where a complete mitral valve closure was postulated. The M-scan beam has limited lateral resolution. It has finite width which at the level of the mitral valve apparatus may be of the order of 1 cm and allows the chordae and papillary muscles to be recorded simultaneously. Papillary muscles may therefore appear artefactually to be interposed between chordae, and buckling of the chordae is not necessary to explain its presence.

The exact cause of abnormal papillary muscle and chordal motion producing 'SAM' has not been explained. Left ventricular hypertrophy including papillary muscle hypertrophy, with resultant papillary muscle displacement at reduced left ventricular transverse dimension may be a factor in hypertrophic cardiomyopathy.^{75,92} However, three patients in this series, who had a normal posterior wall thickness in M-scanning, had a definite 'SAM' which was complete in one patient. Furthermore, 'SAM' has been described in a variety of conditions, many unassociated with significant left ventricular hypertrophy. A common feature of these conditions is a vigorously contracting left ventricular posterior wall. This may be due to generalised hyperkinesia, as in aortic or mitral regurgitation, ventricular septal defect and constrictive pericarditis or to a localised compensatory apical hyperkinesia as seen in reduced or reversed upper septal motion in right ventricular volume overload,^{90,95} or in coronary artery disease with partial

left ventricular wall dyskinesia or left ventricular aneurism.⁷⁰ This understanding of 'SAM' has recently gained further support by a large experimental study on dogs and cats. It has been shown that 'SAM' and functional subaortic stenosis could be provoked by a combination of administering positive inotropic drugs and reducing afterload by controlled bleeding.⁹⁶ Therefore it may be postulated that it is this vigorous contraction of the posterior wall of the apical left ventricle which is the main cause of the abnormal papillary muscle and chordal motion, and that this may be compounded by left ventricular hypertrophy due to any cause. This could also explain the influence on the amplitude of 'SAM' by Beta-adrenergic blockade,^{61,68} and the lack of consistent correlation found between 'SAM' and left ventricular outflow tract obstruction.^{57, 64,70,72,77,98} The major factor in the mechanism of left ventricular outflow tract obstruction is thought to be the velocity of left ventricular ejection as discussed elsewhere.¹⁰⁰

Further support may also be provided by impressions of chordae tendineae on the left ventricular septum as observed in a post-mortem specimen on a patient with hypertrophic cardiomyopathy (Michael Davies, London, personal communication). Hypertrophy of papillary muscles and left ventricular posterior wall may facilitate the systolic anterior displacement of chordae tendineae by closer and more rigid proximity of both structures, resulting in a higher amplitude of 'SAM'. Patient five in table 6 showed no prominent papillary muscles in real-time B-scanning. This patient exhibited an incomplete 'SAM' in M-scanning as well as patient nine, in whom extensively hypertrophic papillary muscles could be envisaged. Thus 'SAM' does not appear to depend on the presence of thickened papillary muscles. A forceful contraction of the left ventricular posterior wall seems sufficient to displace the papillary muscles anteriorly. Additional papillary muscle and left ventricular hypertrophy may augment the amplitude of 'SAM', but the essential and requisite feature is the presence of a vigorously contracting left ventricular posterior wall. Left ventricular hypertrophy has been shown to influence the experimental production of left ventricular outflow tract

obstruction in man,¹⁰¹ but no echocardiographic examinations were carried out at that time to see whether it also influences 'SAM'. In this study there was no significant correlation between left ventricular hypertrophy and left ventricular outflow tract obstruction.

Having observed complete and incomplete 'SAM' structures in many conditions other than hypertrophic cardiomyopathy, 'SAM' in M-scan echocardiography can no longer be taken as a pathognomonic feature of this disease. In my experience the same is true for asymmetrical septal hypertrophy (ASH)⁹⁰ and therefore one has to look for other signs to make the echocardiographic diagnosis of hypertrophic cardiomyopathy. The localised prominence of septal hypertrophy, moving forcibly towards the apex in systole, which is at right angles to the echo beam and therefore often concealed in M-scan echocardiography¹⁰²⁻¹⁰⁴ and the bright endocardial echo of this septal bulge (see fig. 105) with the relative damping of the adjacent myocardial tissue may be used as a characteristic differential diagnostic feature to separate simple septal hypertrophy from that in hypertrophic cardiomyopathy.⁷⁹ The prominent endocardial echo may be due to localised endocardial fibrosis caused by contact with the mitral valve tips in diastole and chordae tendineae in systole. The relative damping of the septal myocardium is thought to represent a scattering phenomenon due to malalignment of myocardial fibres and arrangement into 'whorls' within the septal bulge.^{80,81} These 'whorls' have been observed in microscopic cross-sections through this particular part of the heart in hypertrophic cardiomyopathy.¹⁰⁵⁻¹⁰⁹ A similar pattern can also frequently be observed in M-scan tracings in patients with this disease (unpublished data). A typical example is seen in fig. 103 where the reflections from the posterior wall and septal myocardial tissue in diastole show a particular linear pattern which changes into complete irregular stippling pattern in systole. This may suggest the same systolic echo-scattering phenomenon from the particular disorientation of the reflecting myocardial fibres during systole. The prominent endocardium can also be observed with appropriate gain settings in M-scanning.

Both patterns can be observed in simple septal hypertrophy as well, but never so striking as in hypertrophic cardiomyopathy. This particular tissue information may in future provide an additional criterium to differentiate simple septal hypertrophy from that in hypertrophic cardiomyopathy, when tissue macro-structure determination techniques with swept frequency ultrasound and other techniques become available to be used in combination with real-time B-scan echocardiography.^{23,110,111}

Abnormally bright echoes from the chordae tendineae are a characteristic feature of the real-time B-scan in hypertrophic cardiomyopathy, but have not previously been described in echocardiography. We have observed this chordal prominence in all cases with longstanding volume or pressure overload in both ventricles. It probably indicates chordal thickening and fibrosis and explains the ease of recording 'SAM' in M-scan echocardiography. This may also explain why 'SAM' echoes are often brighter than those reflected from the mitral valve leaflets in diastole.

It is concluded from this study that the M-scan echographic 'SAM' reflects mainly a systolic anterior motion of the chordae tendineae and/or papillary muscles. The completeness of 'SAM' correlates poorly with the diagnosis of hypertrophic cardiomyopathy, with outflow tract obstruction, mitral regurgitation, left ventricular hypertrophy and thickened papillary muscles. These findings contradict the present assumption that the anterior mitral leaflet plays a significant role in the mechanism of left ventricular outflow tract obstruction. The salient feature of all conditions associated with this abnormal subvalvular motion is left ventricular hyperkinesis. Therefore 'SAM' should not be taken as a specific echographic feature for the diagnosis of hypertrophic cardiomyopathy, but may be regarded as an indicator of hyperkinetic contractility of the apical left ventricular posterior wall.

B. PATHO-PHYSIOLOGICAL IMPLICATIONS OF SEPTAL MOTION IN HYPERTROPHIC CARDIOMYOPATHY

1. Introduction

In hypertrophic cardiomyopathy with and without left ventricular obstruction the thickened and immobile interventricular septum (IVS) has been reported as one of the characteristic features in the M-scan echocardiograms of these patients.^{64, 70, 98, 112} It seems paradoxical that in what is otherwise a hyperdynamic left ventricle^{113, 114} the IVS should show hypodynamic contractility.^{64, 70, 98} Furthermore, although the septal endocardium often exhibits a straight line in M-scanning, the motion pattern within the septal myocardium frequently appears hyperdynamic. Scanning towards the cardiac apex often reveals a more normal pattern of septal motion, and the examples shown in the literature differ considerably in their amplitudes of septal motion. These conflicting observations led to a study using real-time B-scan echocardiography to assess shape and function of the IVS in its entirety.

2. Patients and methods

Twenty patients with the diagnosis of hypertrophic cardiomyopathy were investigated by M- and real-time B-scan echocardiography, as described in the previous chapter. Particular attention was paid to the form and motion pattern of the IVS in these patients.

3. Results

The normal findings in real-time B-scanning are discussed earlier on p.130. A typical example of a realtime B-scan of a patient with hypertrophic cardiomyopathy and an upper septal bulge (USB) is shown in fig. 105. The direction of systolic septal motion in this patient is shown in fig. 109 by superimposing the end-systolic and the end-diastolic frames.

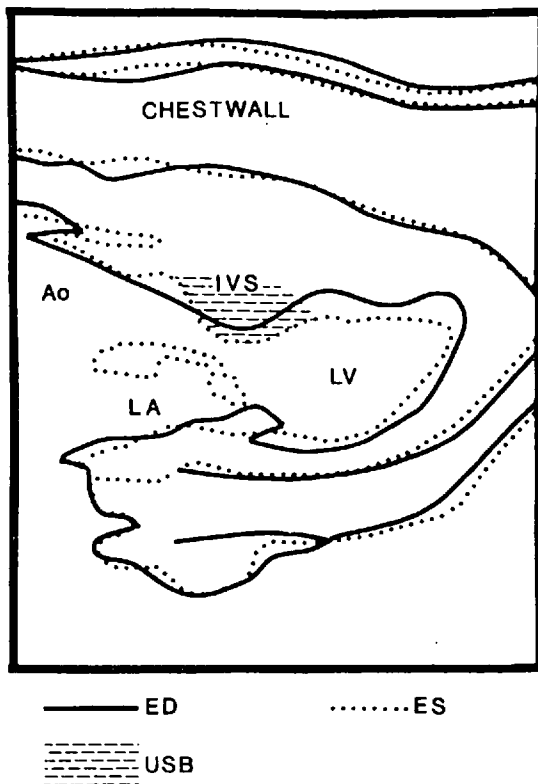


Figure 109. Diagrammatical superimposition of an end-systolic and an end-diastolic frame from a patient with hypertrophic cardiomyopathy and an upper septal bulge which moves mainly towards the cardiac apex and less posteriorly into the left ventricular outflow tract. (Orientation, see fig.104). By permission of Basic Research in Cardiology.¹⁰⁴

The upper septal bulge moves towards the apex instead of moving posteriorly as in normals. There is only slight additional narrowing of the left ventricular outflow tract in systole. The main motion is directed towards the apex. However, the jerky character of this USB motion is only

fully appreciated when viewed in real-time. Fig. 110 shows a standard longitudinal real-time B-scan of a patient with a less prominent and more symmetrically distributed upper septal hypertrophy. Endocardial thickening of the septum can also be seen, and there is marked relative damping of the adjacent myocardial fibres in the area (X).

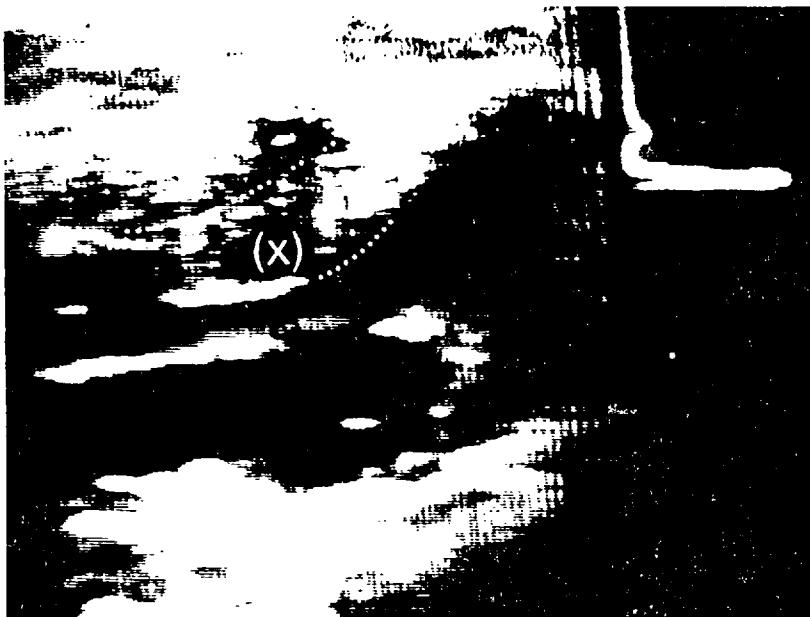


Figure 110. Real-time B-scan of a patient with hypertrophic cardiomyopathy showing a mid-septal bulge(x). (Orientation, see previous figures).

This damping is sometimes less striking, possibly due to fewer histological changes. Table 7 shows the results of this study.

Patient	Age(yrs)	Sex	LVOT grad.	USB	MSB
1	60	M	l	-	+
2	34	M	f	-	+
3	18	M	f	-	+
4	11	M	n.o.	+	-
5	50	M	f	+	-
6	19	M	f	+	-
7	32	F	l	+	-
8	41	M	l	+	-
9	31	M	l	+	-
10	30	F	f	+	-
11	55	M	f	+	-
12	55	F	f	+	-
13	31	F	n.o.	-	+
14	62	F	n.o.	+	-
15	55	M	n.o.	+	-
16	11	M	f	+	-
17	51	F	l	+	-
18	19	M	l	+	-
19	54	F	f	-	+
20	50	F	f	+	-

Table 7. Summary of data obtained from 20 patients with hypertrophic cardiomyopathy showing either an upper septal bulge (USB) or a mid-septal bulge (MSB) during real-time B-scan echocardiography. Abbreviations: yrs=years, M=male, F=female, LVOT grad.=left ventricular outflow tract gradient during catheterisation, l=labile, f=fixed, and n.o.=non-obstructive.

There are twelve males with a mean age of 46 years and eight females with a mean age of 34 years. The mean age of all twenty patients is 39 years. Fifteen patients showed a prominent USB with a maximum thickness within the upper basal third of

the IVS, just below the aortic valve (see fig. 109). Eight of these fifteen patients had fixed, four had labile left ventricular gradients, while only three patients had a non-obstructive form of hypertrophic cardiomyopathy. Five of the twenty patients showed a less prominent USB. Three of these patients had fixed, one had labile left ventricular outflow tract obstruction, and the fifth one was a non-obstructive type. Thus the shape of septal hypertrophy in hypertrophic cardiomyopathy seems non-specific for the type of left ventricular outflow tract gradient. In all patients with upper and mid-septal hypertrophy, bulging into the left ventricular outflow tract, an increasingly jerky motion of this septal bulge towards the apex could be observed, with only a minor component of motion posteriorly, while the lower septal portion near the apex moved normally or hyperkinetically towards the left ventricular posterior wall.

4. Discussion

Considerable discrepancies have been reported by various authors concerning the interventricular septum in hypertrophic cardiomyopathy and its relationship to left ventricular outflow tract obstruction^{62,70,83-85,105,115-122} as recently comprehensively reviewed. Although an intraoperative finding has earlier described the contractile character of the muscular hypertrophy in the left ventricular outflow tract of a patient with hypertrophic cardiomyopathy, as felt by the exploring finger of the surgeon,⁸⁴ the IVS in hypertrophic cardiomyopathy has more recently been believed to be a rather immobile and non-contratile cardiac structure. This has mainly been concluded from the M-scan echocardiogram,^{64,70,98} which indeed can give such an impression, as may be seen in fig. 111. The IVS of this patient with an obstructive type of hypertrophic cardiomyopathy is thickened and the left ventricular endocardial border appears almost as a straight line, giving the impression that no contraction takes place, while the left ventricular posterior wall shows a good amplitude of motion. Only real-time B-scan echocardiography made it possible to understand the discrepancy

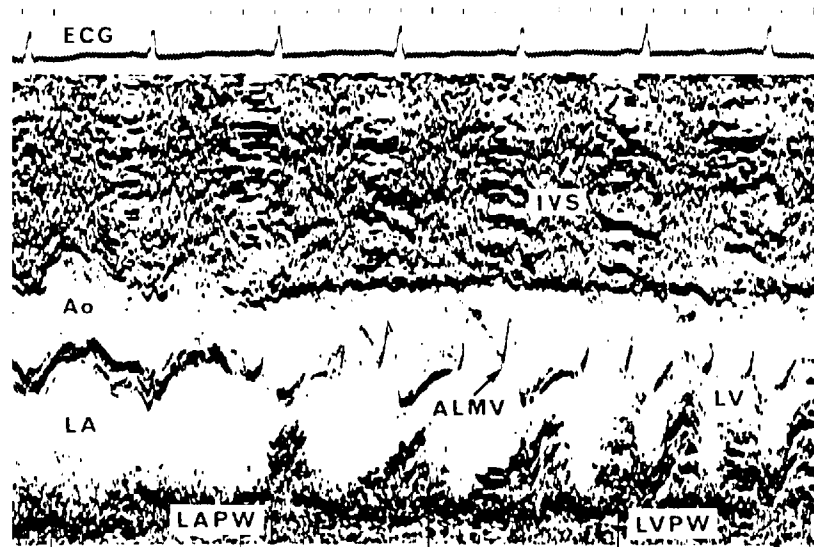


Figure 111. M-scan echogram from a patient with hypertrophic cardiomyopathy. Observing only the left ventricular endocardium of the septum (IVS) one has the impression that it is akinetic, while the aortic root (Ao) and the transition zone between left atrial and left ventricular posterior wall (LAPW, LVPW) are hyperkinetic. (LV=left ventricle, LA=left atrium, ALMV=anterior leaflet of the mitral valve). By permission of Basic Research in Cardiology.¹⁰⁴

between the intra-operative finding of a palpable septal contraction and the nearly completely immobile appearance of the septal endocardium during M-scanning. I could observe that the major septal motion of the upper septal bulge in hypertrophic cardiomyopathy is directed towards the cardiac apex, while the lower septum shows normal or hyperkinetic motion towards the left ventricular posterior wall. The significance of these real-time B-scan findings for M-scan echocardiography is demonstrated in fig. 112 and emphasises the importance of understanding the physics of ultrasound in relation to transducer position. In the upper panel a diagrammatical representation of a longitudinal cross-section through the heart of a patient with hypertrophic cardiomyopathy is shown. The upper septal bulge, shown by a cross-hatched area, contracts mainly towards the apex as indicated by the horizontal arrows. In single dimensional echocardiography the true amplitude of moving acoustic interfaces is recorded only when their motion is parallel to the direction of the ultrasonic beam.⁹⁸

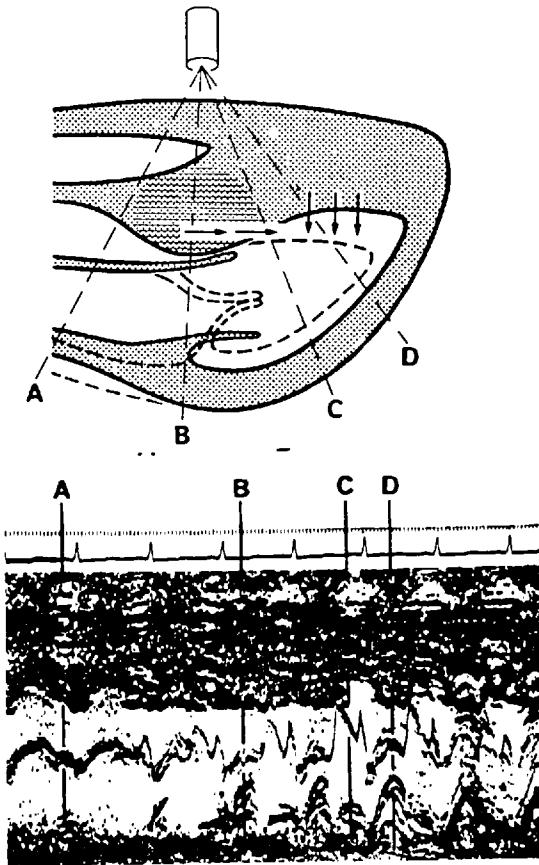
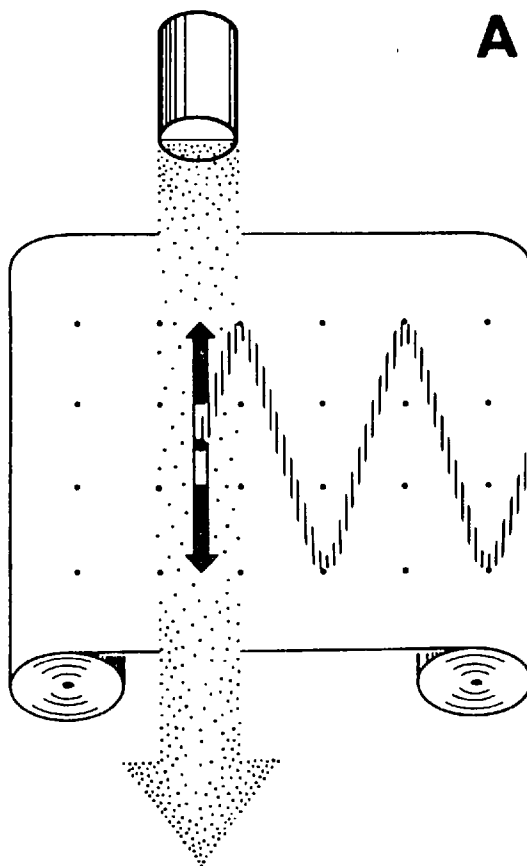


Figure 112. The upper panel shows a diagrammatical representation of a longitudinal cross-section through the heart of a patient with hypertrophic cardiomyopathy. The upper septal bulge, with cross-hatched area, is indicated to move mainly towards the apex while the apical septum moves posteriorly. Four main beam directions are displayed (A-D). The lower panel shows a continuous M-scan sweep from the aortic root into the left ventricle and the transducer directions A-D accordingly. The USB moves perpendicular to the echo beam B and can therefore not be appreciated according to its true amplitude of motion. A normal pattern of motion is observed in the transducer positions A and D, while at C an abrupt change between the positions B and D is noticed. By permission of Basic Research in Cardiology.¹⁰⁴



This is explained in fig. 113. With an increasing angle between the direction of the beam and the moving target the amplitude of motion will decrease (fig. 114) and will be reduced to zero when the beam is perpendicular (fig. 115). With an angle beyond 90° the amplitude will increase again to reach the original true representation of structure motion at 180° , however, with reversed direction. The

Figure 113. Diagrammatical representation of an object (point) moving parallel to the ultrasonic beam (dotted arrow). The amplitude of motion (black arrow) is fully recorded on the M-scan strip chart. See figs. 114 and 115.

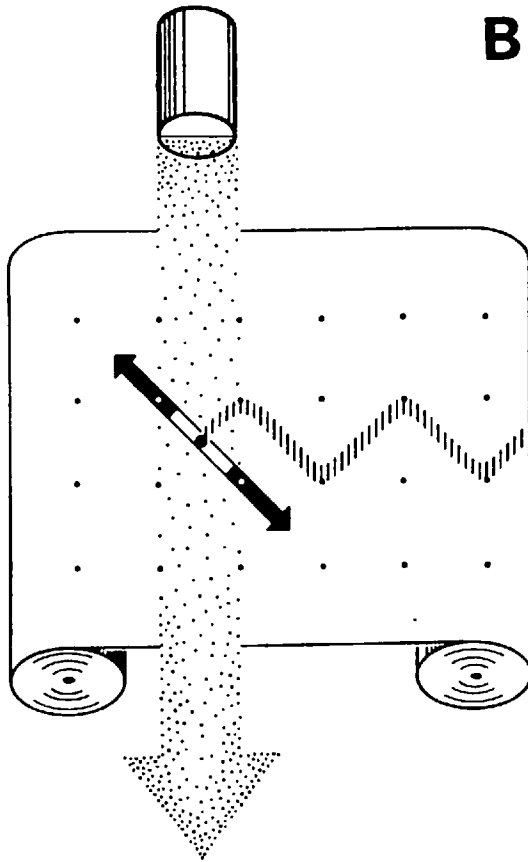


Figure 114. Diagrammatical illustration of the object in fig. 113, moving diagonally to the direction of the ultrasonic beam. Only the amplitude of motion in relation to the beam direction and limited by beam width is recorded on the chart.

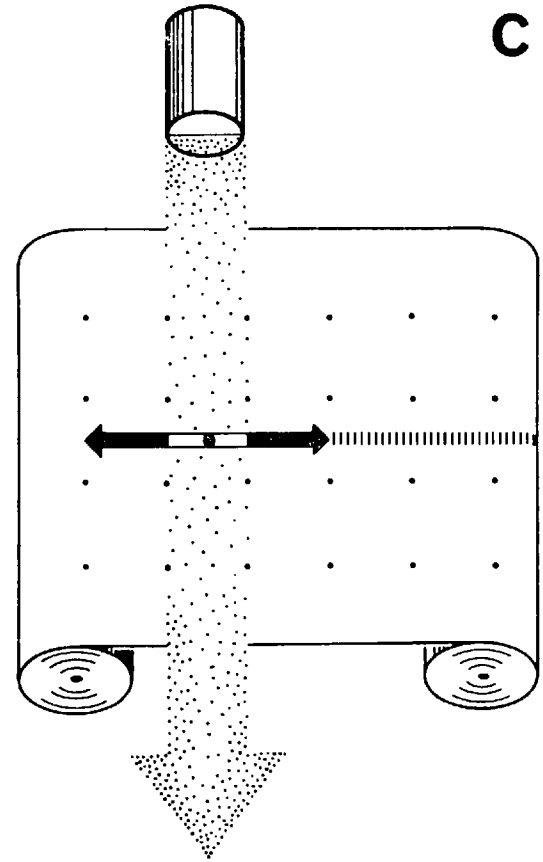


Figure 115. Diagrammatical illustration of the object in figs. 113 and 114, moving perpendicular to the ultrasonic beam. Since no movement is occurring relative to beam direction, no amplitude of motion is recorded on the strip chart.

movement of the upper septal bulge in figs. 105 and 112 is more or less at right angles to the single ultrasonic beam and can therefore not be appreciated in its true amplitude of motion. Depending on beam direction, a normal motion will be observed in the region of the aortic root (A) and aorto-septal transition zone in fig. 112, and an apparently immobile endocardium at the beam direction (B). It is interesting to note that the echo pattern within the IVS in the M-scan suggests a great deal of activity, which shows that little attention has been paid to tissue identification and differentiation in this disease. It also suggests that the USB is not adynamic

but mobile. Between the directions (C and D) lies the transition zone from the horizontally moving upper septal bulge to the apical portion which moves relatively normally, i.e. posteriorly. This transition is recorded in M-scanning (lower panel of fig. 112) as an abrupt change from an 'immobile' to a mobile appearance of the interventricular septum in the middle of a cardiac cycle. Pointing the transducer further towards the cardiac apex (D) a 'normal' posteriorly moving septum will be recorded, however, with a reduced amplitude of motion at this oblique angle. Thus, observing a mobile septum in an M-scan echocardiogram recorded from the normal transducer position on the chest does not exclude the diagnosis of hypertrophic cardiomyopathy, unless the entire IVS has been visualised by a complete M-scan sweep, which allows the relative position of the transducer to be recognised. The IVS may also be recorded with a more normal pattern of motion during the entire continuous M-scan sweep if the transducer were angled from the cardiac apex (compare fig. 112).

The haemodynamic significance of these M- and real-time B-scan echographic findings for the evaluation of left ventricular function from the M-scans of patients with hypertrophic cardiomyopathy has recently been reported in preliminary form.¹⁰³

The real-time B-scan echographic findings of the typical upper septal bulge motion in hypertrophic cardiomyopathy may also shed light on part of the mechanism involved in the development of a left ventricular outflow tract gradient, as illustrated in fig. 116. The diagrammatical representation of a longitudinal cross-section of a patient with an upper septal bulge is shown in systole (continuous lines) and diastole (broken lines) to indicate the systolic motion of the upper septum mainly towards the cardiac apex. The arrows are meant to indicate a possible concentration of systolic pressure forces towards the apical left ventricle (where the lowest catheter tip has been positioned, introduced from the aortic root). This concentration may be particularly facilitated by the upper septal bulge motion, preventing the transmission of the left ventricular systolic pressure to the outflow chamber by increasing turbulence and thus supporting the development

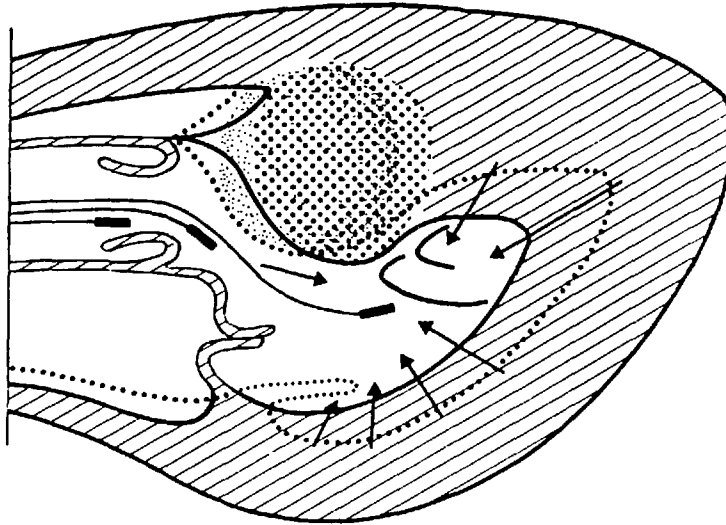


Figure 116. Diagrammatical representation of a longitudinal cross-section through a heart with hypertrophic cardiomyopathy in diastole (broken lines) and systole (continuous lines). The upper septal bulge is indicated to move mainly towards the apex in systole and thus appears to contribute to a concentration of systolic pressure forces (arrows) in the apical left ventricle, in the vicinity of the lowest catheter tip manometer introduced through the aortic root. A high velocity of left ventricular ejection must result, which may produce turbulence in the outflow tract. ¹⁰⁴ By permission of Basic Research in Cardiology.

of a pressure difference on either side of the bulge (between the two lower catheter tip manometers in fig. 116). It is not suggested that this septal motion is the main mechanism of left ventricular outflow tract obstruction, since the shape of septal hypertrophy seems independent from the type of left ventricular outflow tract obstruction. It appears to be one particular factor which may explain why the left ventricle is able to empty up to 80% of its stroke volume within the first half of left ventricular ejection time.¹²³ We have previously suggested that the velocity of left ventricular ejection appears to be the main factor in the development of left ventricular outflow tract gradients in hypertrophic cardiomyopathy.^{99,100} If this theory is correct, then labile or even fixed left ventricular outflow tract gradients should also be found in patients without hypertrophic cardiomyopathy where hyper-

kinetic left ventricular ejection is present. This has indeed been recently supported by findings of small left ventricular outflow tract gradients in systole in patients without hypertrophic cardiomyopathy but with hyperdynamic left ventricles.¹²⁴

The malalignment of myocardial fibres within the interventricular septum, in particular in patients with resting gradients, has been described as a formation of 'whorls' and as a fairly reliable histological guide to the diagnosis of hypertrophic cardiomyopathy.^{106,108} The finding of a bright endocardial border of the upper septal bulge in real-time B-scanning, as seen in fig. 105, with a relative damping of adjacent echoes from myocardial tissue may reflect the localised endocardial fibrosis caused by contact with the anterior mitral valve leaflet in early diastole and of chordae tendineae in systole, and also the histologically proven malalignment of myocardial fibres in this region.^{81,125} Regularly and parallel aligned myocardial fibres consistently reflect ultrasonic waves which produce a uniform tissue pattern on the oscilloscope (see fig. 104). If such an arrangement is altered, e.g. into a 'whorl' formation of fibres, ultrasonic waves will be reflected in all directions according to the particular angle at which each layer presents itself in relation to the ultrasonic beam. The mode of reflection in all directions may be understood as a scattering phenomenon, and may thus be responsible for the damping seen in the upper septal bulge in hypertrophic cardiomyopathy. A similar but far less striking pattern of endocardial brilliance and adjacent damping of myocardial echoes may also be seen in cases other than hypertrophic cardiomyopathy.¹²⁶ These findings together with the typical change in direction of upper septal bulge motion suggest that there may be an underlying mechanism for this change in contraction in order to prevent additional narrowing of the left ventricular outflow tract in systole, but nevertheless to allow this part of the interventricular septum to contribute to rapid left ventricular ejection. The motion of the USB may be an active process of contraction or the malalignment of myocardial fibres may cancel out any resultant motion of this bulge, which may then be moved passively towards the cardiac apex by

the fibrous ring during apex to base contraction of the heart. It is suggested that the relative myocardial damping within the septum in real-time B-scan echocardiography, often seen as a scattering phenomenon with reduced intensity in M-scanning as well, may be the echographic representation of the histological changes, which in turn could be believed to be a manifestation of the underlying patho-physiological mechanism of septal motion in hypertrophic cardiomyopathy.

C. SEPTAL MOTION IN HYPERTROPHIC CARDIOMYOPATHY: IMPLICATIONS FOR THE ACCURACY OF FUNCTIONAL ASSESSMENT BY M-SCANNING

1. Introduction

The interventricular septum (IVS) in hypertrophic cardiomyopathy has been shown in the previous chapter to be mobile, which contradicts earlier reports based on M-mode echocardiography.

The purpose of this study is to assess the effect of this characteristic septal motion in this disease on the usual functional indices derived from the M-mode scan.

2. Methods and material

Ten patients with hypertrophic cardiomyopathy in whom the diagnosis was confirmed by left ventricular catheterisation and angiography, and in whom the upper septal bulge (USB) was seen to move towards the apex in real-time B-scanning were investigated by M-scan echocardiography. The left ventricular internal diameters were measured at the apparently immobile USB and then lower down towards the apex where a more normal direction of septal motion was seen. The shortest possible diameter was chosen for end-systole and the diameter at the peak of the simultaneously recorded R-wave for end-diastole. The ejection time was measured from the M-scan, from the beginning of the anterior motion of the left ventricular posterior wall endocardium to the summit of this movement. Fig. 117 represents an M-scan echocardiogram of a patient with hypertrophic cardiomyopathy, illustrating the change of left ventricular internal diameter, when directing the transducer from the lower septum towards the prominent USB. It can be readily appreciated that in the lower septum, where a normal pattern of motion is seen, the diastolic internal diameter (D_1) is considerably larger than D_2 at USB level. It is also interesting to note that the C point at D_1 is nearer to the left ventricular posterior wall than to the septum, while it

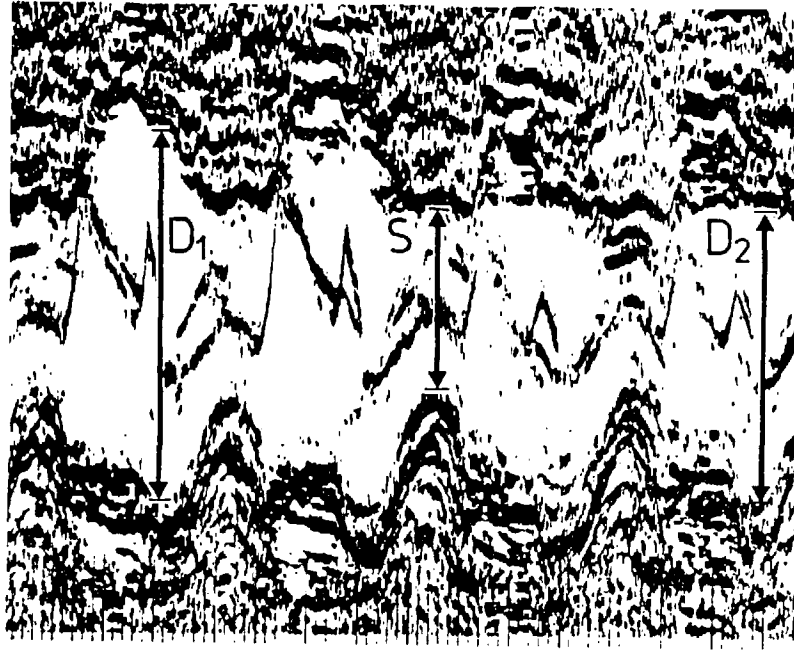


Figure 117. M-scan echocardiogram of a patient with hypertrophic cardiomyopathy illustrating the change in left ventricular internal diameter (end-diastole D_1 and D_2) when directing the transducer from the lower IVS towards the prominent upper septal bulge. By permission of Thieme Verlag.¹⁰³

is half way between septum and posterior wall at D_2 . There is little change between the systolic dimensions at S and the two systolic complexes before S.

3. Results

The M-scan echographic measurements of mean end-systolic and end-diastolic diameters (ESD and EDD) are shown in table 8. The measurements a. were taken in the region of the USB or the apparently immobile septum, while the measurements b. were taken lower towards the apex, where a normal septal motion pattern was seen. From these measurements the end-diastolic and the end-systolic volumes (EDV and ESV) were calculated according to different formulae,^{127,128} using the cubed method, indicated for end-diastolic volumes by EDD^3 ; the second volumes were calculated according to the formula given by Popp and

Mean values of left ventricular internal diameters (n=10/20) and functional indices at upper septal bulge (a.) and lower septum (b.)

	EDD (cm)		ESD (cm)		EDV (ml)		EDV (ml)		ESV (ml)		ESV (ml)		
					(EDD ³)		(EDD ³ x1.047)		(ESD ³)		(ESD ³ x1.047)		
	a.	b.	a.	b.	a.	b.	a.	b.	a.	b.	a.	b.	
$\bar{x}$	4.47	3.67	2.65	2.34	93.5	54.2	97.9	56.7	18.7	15.0	19.6	15.8	
S.D.	0.57	0.69	0.63	0.55	36.3	28.3	38.0	30.0	10.3	10.3	11.0	11.0	
S.E.M.	0.18	0.22	0.20	0.17	11.5	8.9	12.0	10.0	3.3	3.3	3.5	3.5	
T	4.35		2.01		4.68		4.71		2.2		2.2		
P	0.002		0.08		0.001		0.001		0.06		0.06		
	SV (ml)		SV (ml)		EF (%)		EF (%)		fract. Vcf.		mean Vcf.		E.T.
	(LVID ³)		(LVID ³ x1.047)		(LVID ³)		(LVID ³ x1.047)		(%)		(circ./sec.)		(sec)
	a.	b.	a.	b.	a.	b.	a.	b.	a.	b.	a.	b.	
$\bar{x}$	74.8	38.8	78.3	40.9	76.7	67.4	76.6	67.6	45.5	39.1	1.18	1.02	0.31
S.D.	40.9	27.7	42.9	30.2	15.8	21.3	15.9	22.0	16.2	15.0	0.61	0.55	
S.E.M.	13.0	8.7	13.6	9.6	5.0	6.7	5.0	7.0	5.1	4.7	0.19	0.17	
T	4.2		4.3		2.2		2.1		2.98		1.19		
P	0.002		0.002		0.05		0.07		0.02		0.26		

Table 8. Mean results of septal M-scan measurements in the region of the upper septal bulge and below. (EDD, ESD=end-diastolic and end-systolic diameter, ESV, EDV=end-systolic and end-diastolic volume, EF=ejection fraction, Vcf=velocity of circumferential fibre shortening, ET=ejection time; $\bar{x}$ =mean value (n=10), S.D.=standard deviation, S.E.M.=standard error of the mean, T=T statistic from paired T-test, p=significance)

Harrison,¹²⁷ indicated by $EDD^3 \times 1.047$. From these measurements stroke volumes (SV) and ejection fractions (EF), fractional (fract. Vcf.) and mean velocity of circumferential fibre shortening (mean Vcf.) were calculated. The mean ejection time was 0.31 sec.

Table 9. shows the mean differences when measuring the internal diameters firstly at the USB level and then lower towards the apex. The mean difference for end-diastolic diameters was 8 mm, which means a 22% change. Employing the 2-tailed test of significance this difference was significant with a p-value of 0.002. For end-systolic diameters the mean difference was 3 mm, which means a 13% change, also significant. There was a 70% change for end-diastolic volumes, whereas only a 5% change for end-systolic volumes. The percent change in

RESULTS (M-scan)
(2-tail test of significance)

USB → lower IVS	Mean difference	Percent change	P =
EDD ↑	8mm	22	0.002
ESD	3mm	13	0.08
EDV (EDD ³) ↑	40ml	70	0.001
EDV (" x 1.047) ↑	41ml	70	0.001
ESV (ESD ³) ↑	3.7ml	25	0.06
ESV (" x 1.047) ↑	3.8ml	24	0.06
SV (EDV-ESV) ↑	36ml	93	0.002
SV (" x 1.047) ↑	37ml	91	0.002
EF $\left \frac{\text{EDV-ESV}}{\text{EDV}} \right $ ↑	9.3%	14	0.005
EF (" x 1.047) ↑	9.0%	13	0.007
fr. Vcf $\left \frac{\text{EDD-ESD}}{\text{EDD}} \right $ ↑	6.4%	18	0.02
m. Vcf $\left \frac{\text{EDD-ESD}}{\text{EDD} \times \text{E.T.}} \right $ ↑	0.16cps.	16	0.26

Table 9.

Mean difference and percent change in M-scan measurements at upper septal bulge (USB) level and below in patients with hypertrophic cardiomyopathy. The resulting functional parameters may show differences up to 93%. See abbreviations in table 8.

stroke volumes was above 90%, and the lowest value was seen for ejection fraction. The change for fractional Vcf was 18% and statistically significant, while it was 16% for mean Vcf, which was no longer significant.

4. Discussion

The results in table 8 and the summary in table 9 show the large differences which may occur in the measurements of left ventricular internal dimensions and the functional indices calculated from these data in patients with hypertrophic cardiomyopathy. Cubing the dimensions to calculate volumes, whatever formulae may be used,¹²⁸ produces an even greater percentage difference up to 93% in this study, so that volume calculations must be regarded as highly inaccurate in these patients. It is generally agreed that the short axis of the left ventricle cannot be used to measure volumes,^{129,130,131} but even other indices which are thought to be reliable and still

used today, like fractional and mean Vcf, may vary by about 20%. The fact that the apparent movement of the septum can vary so greatly in patients with hypertrophic cardiomyopathy during a standard M-scan echographic investigation means that all functional data based on this type of study should be accepted with great caution. The presence of a mobile and thickened interventricular septum, judged from only a limited area of the heart in M-scanning, should not exclude the possible diagnosis of hypertrophic cardiomyopathy, unless the mobility of the entire septum has been shown in a complete continuous sweep tracing. During such a sweep the USB will appear as a straight line when moving at right angles to the single ultrasonic beam, as seen earlier in fig. 112. This can also be misleading when observing the USB in transverse cross-sections of real-time B-scan echocardiography, as indicated in fig. 118 with two M-scan transducer positions. Real-time B-scanning

would record only the minimum amplitude of motion towards the left ventricular posterior wall and may thus mislead the novice to state an a- or hypo-

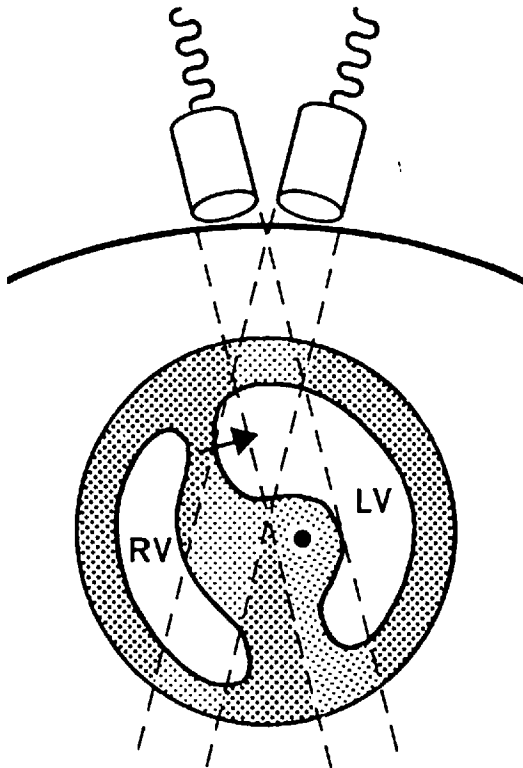


Figure 118. Diagrammatical representation of a transverse cross-section through the septal bulge in hypertrophic cardiomyopathy, and of two single beam transducer positions. One must imagine the black dot moving together with the upper septal bulge towards the observer's eye, which accounts for an apparent hypokinesis of this structure, as this direction of motion cannot be recorded by the beam. Adjacent part of the left ventricle (arrow) may show relatively normal amplitude of motion.

kinetic septal motion in order to confirm previous erroneous M-scan assumptions. Different transducer directions during single beam echocardiography, as indicated by the two transdu-

cers in fig. 118, may result in different amplitudes of septal motion depending on whether the beam records the USB or more lateral parts of the septum. In addition, if the transducer is directed more from the cardiac apex and a longitudinal continuous M-scan sweep is carried out in the longitudinal plane (see fig. 112), a relatively normal amplitude of motion may be recorded during the entire sweep.

These difficulties make it obvious that the particular features of hypertrophic cardiomyopathy are much more readily appreciated with real-time B-scanning than with M-scanning. The findings in these studies highlight the complexity of the abnormality in this disease, and it is only by using techniques such as two-dimensional real-time echocardiography, encompassing as much of the heart as possible in many different cross-sectional planes, that a more complete picture of the disordered left ventricular anatomy and function is obtained.

D. CONCLUSION

Real-time B-scanning has changed the non-invasive diagnostic criteria of hypertrophic cardiomyopathy, and allows a new insight into the pathophysiological events in this disease. Thus the prevailing schools of thought over the last 15 years are re-evaluating their concepts and will most probably find a new classification for hypertrophic myocardial disease of unknown origin. This seems all the more important since the increasing sensitivity of the echographic techniques has pointed out similar structural and also haemodynamic appearances in patients with simple or secondary septal hypertrophy, which has increased the difficulties in the differential diagnosis of this disease. The findings presented may also lead to a new or earlier therapeutical intervention in these patients, which have been regarded by some authorities to need therapy only when symptomatic. Many more problems in this controversial heart condition will have to be solved in the future and real-time B-scanning in conjunction with M-scan echocardiography will certainly play an important role

in the diagnostic evaluation of patients with hypertrophic cardiomyopathy.

CONCLUSIONS

Of all two-dimensional echographic techniques real-time B-scanning appears to be the non-invasive method of choice for investigating patients with cardiac abnormalities, since the changes not only of true anatomical relationships but also of overall contractile behaviour of the heart and of particular regional areas may provide diagnostic clues which are often not equalled by angiocardiography. Flow within the heart may also be evaluated by additional peripheral injection of saline, blood or contrast media, so that, with progressive knowledge and critical understanding of the limitations of the two-dimensional scanning technique, real-time B-scan echocardiography may become the most frequently used diagnostic tool in future ambulant and clinical cardiology. It is already and will further be replacing angiocardiography in those cases where pressure measurements are not the most important data for assessing the appropriate medical and surgical means of therapy. Real-time B-scanning will not replace angiocardiography entirely and probably never coronariography, but it has already reached a comparable place alongside angiography for diagnostic purposes in centres which fully understand this method and its diagnostic potential. In those centres it will soon replace also M-scan echocardiography, a method which will probably be used in future as an adjunct to real-time B-scanning for particular time related questions where higher resolution in space and time may be of importance.

INDEX OF ABBREVIATIONS

1

AAW: anterior aortic wall
AAo: anterior aortic root
ALMV: anterior leaflet of the mitral valve
Ao: aorta
a-p: anteroposterior
AR: aortic regurgitation
ASH: asymmetric septal hypertrophy
CBS: conventional B-scanning
Ch: chordae tendineae
COCM: congestive cardiomyopathy
CRT: cathode ray tube
CST: continuous sweep technique
ECG: electrocardiogram
EDD: end-diastolic diameter
EDV: end-diastolic volume
EF: ejection fraction
Endo.: endocardium
ESD: end-systolic diameter
ESV: end-systolic volume
ET: ejection time
f: female
H: head
HCM: hypertrophic cardiomyopathy
IVS: interventricular septum
L: limb
LA: left atrium
LA/LV-TZ: transition zone between left atrium and left ventricle
LAO: left anterior-oblique
LAPW: left atrial posterior wall
LCC: left coronary cusp
L_D: long axis in diastole
L_S: long axis in systole
LV: left ventricle
LVID: left ventricular internal diameter
LVOT: left ventricular outflow tract
LVPW: left ventricular posterior wall
m: male
MR: mitral regurgitation

MSB: mid-septal bulge
MVL: mitral valve leaflet
NCC: non-coronary cusp
p: significance
PAo: posterior aortic root
PAW: posterior aortic wall
Pl: placenta
PLMV: posterior leaflet of the mitral valve
PM: papillary muscle
PR: prolapse
PW: posterior wall
RA: right atrium
RAO: right anterior-oblique
RTBS: real-time B-scan
RV: right ventricle
RVAW: right ventricular anterior wall
RVOT: right ventricular outflow tract
SAM: systolic anterior motion
S.D.: standard deviation
S.E.M.: standard error of the mean
SV: stroke volume
TBS: triggered B-scan
Tr: transducer
T=T: statistic from paired T-test
USB: upper septal bulge
Vcf: velocity of circumferential fibre shortening
vCh: virtual chordae

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