tire short axis of the left ventricle, it is often inadequate in
displaying the entire long axis of the same ventricle. Current
modifications and developments are oriented toward over-
coming these limitations in an effort to produce even more
diagnostically useful images which will permit accurate
quantification of various cardiac geometries and functions.

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Cardiac Imaging Using a
Phased Array Ultrasound System

II. Clinical Technique and Application

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SUMMARY A new two-dimensional ultrasound imaging system
that capable of producing high resolution tomographic images of the heart
in real time has been developed. This system relies on phased array
principles to rapidly steer the ultrasound beam through the structures
under investigation. A hand-held linear array of 16 ultrasound
transducers with overall dimensions of 14 mm by 24 mm at the site
of contact may be readily manipulated to image various cardiac
structures. The resulting images are displayed in a circular sector format,
60° in azimuth and typically 15 cm in range. At this maximum range,
image frames consisting of 256 lines are generated at the rate of 20
frames/second. High azimuthal resolution throughout the field of
view is assured by a focused transmit beam and by sweeping the focus
of the receiver in synchrony with the range of returning echoes. Azimuthal
resolution varies from 2 to 4 mm throughout the field of view
while range resolution is 1.5 mm. This imaging system has proven
particularly useful for the delineation of left ventricular spatial
geometry by the identification of endocardium, myocardium, papillary
muscles and interventricular septum. High quality images of
anterior and posterior mitral leaflets, aortic root and aortic leaflets
as well as left atrium and other cardiac structures have been obtained.

ONE DIMENSIONAL time-motion echocardiography has
been extraordinarily useful in the assessment of certain cardiac
disorders.1 This widely available ultrasound technique,
however, is unable to supply detailed information concerning
spatial geometry. As a result, several two-dimensional
ultrasound imaging systems have been developed for cardiac
use over recent years. This report presents the initial clinical
results from a new, high-resolution, real-time, two-dimen-
sional ultrasound sector scanner designed specifically for
cardiac use.

Methods

Equipment

Echocardiographic studies were performed using a two-
dimensional imaging system developed in the Duke University
Biomedical Engineering Department. This system relies
on phased array principles to rapidly steer the ultrasound
beam through the target volume and is capable of producing
high-resolution, tomographic images of the heart in real-
time. A hand held linear array of 16 transducers, measuring
14 mm by 24 mm at the site of skin contact, may be readily
manipulated into appropriate planes for imaging a variety of
cardiac structures. The resulting images are displayed in a
sector format. The maximum selectable field of view
is 60 degrees in azimuth and 17 cm in range. At this
maximum range, image frames consisting of 256 lines are
generated at the rate of 20/second. High azimuthal resolu-
tion throughout the field of view is assured by sweeping the
focus of the receiver in synchrony with the range of returning
echoes. Azimuthal resolution varies from 2 to 4 mm
throughout the field of view while range resolution is 1.5
mm. A digital computer controlled scan format provides
high data acquisition rates suitable for imaging rapidly mov-
ing cardiac structures. The 60 degree sector arc provides a
wide field of view. When operating in a mode synchronous
with television rates, images are usually made up of 128 lines
per frame. When operating asynchronously, the system is

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capable of images composed of 256 lines per frame. One centimeter range marks may be introduced at any time during the scan process.

A silicon diode television camera records the images from a display monitor and a permanent video tape recording is then made of each examination for later review and analysis. Single frame images presented in this manuscript were made by means of a standard 35 mm camera from single frame video tape recordings.

Patients

Images presented in this manuscript are from the first seventy patients examined with this system at the Duke Hospital. The patients underwent echocardiographic evaluation for a variety of clinical problems including rheumatic valvular, congenital and atherosclerotic heart disease. During these initial phases of clinical trial, a variety of scan formats (e.g., varying line density), transducers, and display and recording devices were utilized and thus account for variations in the image quality seen in figures 3 through 9.

Examination Technique

In the present system design two operators are necessary to perform an ultrasound examination. The first operator manipulates the hand-held transducer while the second operator adjusts the image quality (time gain control, overall gain and range) while managing the video tape recording system.

Ultrasound examinations were performed with patients in the supine (fig. 1) or left lateral positions. The transducer is placed over an aquasonic gel interface to the left of the sternal border between the 2nd and 5th ribs and costal cartilages. An identical acoustic window to that used for time-motion examination of the heart is then utilized. Most favorable images, of course, are recorded when the transducer is held over an intercostal space rather than over the ribs, costal cartilages or sternum.

A standard echocardiographic examination is performed in a number of cross-sectional planes through the heart (fig. 2). Position I usually reveals images through the long axis of the left ventricle (aortic root, aortic valve, left atrium, mitral leaflets and the left ventricular cavity). Position II reveals portions of the right atrium, tricuspid leaflets and right ventricle in long axis. Serial cross-sectional images through the short axis of the heart are then made. Position III is through the short axis of the great vessels and atria, usually at the level of the aortic valve. Position IV provides an image through the short axis of the left ventricle at the level of the mitral orifice. Position V provides a short axis view of the left ventricle at the level of the papillary muscles while position VI is a similar view at the level of the left ventricular apex.

As chest wall configuration and intrathoracic heart position are quite variable from patient to patient, a study is initially begun by locating the aortic root, mitral valve and portions of the left ventricle in long axis (position I). From that point the remaining cardiac structures are then located by manipulating the transducer into the previously described positions II–VI and other appropriate intermediate positions.

Results

Image Recording Process

As previously mentioned, the images presented in this manuscript are 35 mm still photo recordings of single frame images from video tape. As such, there is a loss of the visual integration of motion normally seen with the real-time recording. Moreover, there is a severe degradation in image quality caused by the video tape recording process. An individual field from the TV tape recording represents only 1/60th of a second. When operating in the 128 line format, therefore, each single frame visual field represents only one half (or 64 lines) the information provided in the actual scan or in real-time playback.

Results of Cardiac Imaging

Figure 3A shows a typical scan through the long axis of the left ventricle (position I). Cardiac structures are labelled in the schematic conception of the image in Figure 3B. The heart is in diastole with the aortic cusps in the closed position and the mitral leaflets in the open position. Details of the papillary muscles and chordae tendineae are seen along with echoes from the endocardial and epicardial surfaces. A large posterior pericardial effusion is seen.

Figure 4A shows a long axis scan (position I) through the left ventricle of a patient with an atrial septal defect. Cardiac structures are labeled in figure 4B. The heart is in systole. Note the large right ventricle anteriorly. The entire left ventricle is visualized in long axis from the aortic root to the apex. The left atrium is appropriately small.

Figure 5 compares diastolic (5a) and systolic (5b) frames through the long axis of the aortic root and mitral valve in a patient with mild pulmonary hypertension. The aortic cusps are well seen in the closed position while the mitral leaflets are seen in the open position in figure 5a. Figure 5b shows the ventricle in systole with one aortic cusp in the open position and both mitral leaflets in the closed position. The arrow points to a structure in the posterior A-V groove that may represent either coronary sinus or a prominent A-V groove circumflex coronary artery. This image was recorded with an early scan format (256 lines) using a vidicon TV
camera and differs in quality from the others presented.

Serial short axis cross sections through the left ventricle are shown in figure 6. Panels A and B show an image through the mitral orifice in diastole (position IV). Panels C and D show a short axis cross-sectional image through the level of the papillary muscles (position V). Note the details of the papillary muscle trabeculations seen in this frame. A pericardial effusion is also seen. Panels E and F show a short axis scan at the level of the left ventricular apex. The small ventricular cavity and the base of the papillary muscles are seen at this level. Note that the scan format is of the variety seen in figure 5a.

**FIGURE 2** Schematic diagram showing six standard planes for viewing the heart. A variety of intermediate planes may also be used. Note the location of the transducer top. This will locate the position of the top of the sector arc presented in subsequent figures. For further description, see text.

**FIGURE 3** Panel A shows a photo from a stop action video tape frame through the long axis of the left ventricle (position I). The aortic root is at the top of the scan and the left ventricular body toward the bottom. Note the pericardial effusion. AoR = aortic root; AoV = portion of aortic leaflets in diastole; RVC = right ventricular cavity; S = interventricular septum; PM = papillary muscles; LVC = left ventricular cavity; PE = pericardial effusion; LA = left atrium; AML = anterior mitral leaflet; PML = posterior mitral leaflet; EN = endocardium; EP = epicardium; and P = pericardium.

**FIGURE 4** Panel A shows a scan through the long axis of the left ventricle (position I) in a patient with an atrial septal defect. Note the large right ventricular cavity. The entire left ventricular cavity is visualized from aortic root to apex. Abbreviations are the same as in figure 3. For details, see text.
A scan through position IV in a patient with mitral stenosis is seen in figure 7. The arrow points to the anterior mitral leaflet. Note the small mitral orifice size in comparison with that in figure 6A.

An example of abnormal geometry of left ventricular contraction is shown in the paired diastolic and systolic frames in figure 8 (position V). In this patient with severe pulmonary hypertension the left ventricle assumes a rather oval appearance both in systole and diastole. Compare this configuration to the normal circular configuration of the left ventricle seen in figure 6B.

Examination of the tricuspid valve in long section is possible by manipulation of the transducer into position II. Figure 9 shows sequential diastolic (9A), early systolic (9C) and late systolic (9E) frames from a patient with a flail anterior tricuspid leaflet due to acute bacterial endocarditis. This flail leaflet was documented at surgery for tricuspid valve replacement.

Discussion

Since first clinically used in 1954, time motion echocardiography has justifiably enjoyed wide clinical application in the diagnosis of a variety of cardiac disorders. It cannot be assumed, however, that a one-dimensional echo image of a moving heart is a completely fair representation of the details of cardiac anatomy or motion. Indeed, there are two basic reasons to believe otherwise. First, angiographic studies into the complexities of left ventricular contraction clearly indicate that the left ventricle undergoes sequential contraction manifest by a series of rotational and other three-dimensional movements. It is, accordingly, difficult to imagine that data derived from a one-dimensional echo recording faithfully reflects these complexities of motion.

Second, while it is possible to obtain useful information concerning intracardiac spatial relationships by sweeping the ultrasound transducer from structure to structure from a relatively fixed position on the chest wall, it cannot be assumed that these time-motion recordings represent a true picture of the spatial relationships between the targets. The resulting images are, of course, distorted by both the time it takes to perform the sweep and the changing transducer to target distance.

It is not yet possible to describe the actual role of real-time two-dimensional imaging devices in clinical diagnosis. Early reports by Sahn and Henry, however, indicate that such devices show promise in the diagnosis of a variety of cardiac disorders. It is likely that both one and two-dimensional imaging systems will, in time, work effectively together to expand the diagnostic capability of cardiac ultrasound.

The present report concerns results from the initial clinical application of a new ultrasound scanning system. The system is unique and utilizes phased array principles to electronically steer and focus the ultrasound beam and thus develop high-resolution, two-dimensional images of cardiac structures in real-time. To our knowledge, no such imaging system has previously been applied to cardiac use.

Some operational aspects of this imaging device in clinical use are notable. First, the small transducer is relatively easily manipulated on the chest wall, so that there is no need for a cumbersome B-scan arm or mechanical scanning device. There is, therefore, little impairment of sensation in detecting ribs, costal cartilage, sternum or other aspects of chest wall configuration. Severe angulations of the transducer are, however, limited to the size of the present transducer face plate. In order to minimize loss of skin contact, smaller transducer arrays are currently under construction.

Second, the wide field of view (15 cm wide at 15 cm range), is superior to that provided by mechanical sector scanners. An added advantage of the wide sector arc is that it allows visualization of substernal structures such as the tricuspid valve and the right atrium when the transducer is held adjacent to the sternum and angled in position II.

Third, the ultrasonic images are of high resolution and high line density. Unfortunately, the image is significantly degraded in the video tape stop-frame mode and subsequent photographic processes necessary to capture an image for publication. Moreover, real-time playback of these images provides a visual integration of cardiac motion not possible to experience in the stop-frame mode.

Fourth, the computer controlled scan process provides a unique flexibility for future expansion of system capabilities.

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Figure 5 Paired diastolic (panel a) and systolic (panel b) scans in position I in a patient with mild pulmonary hypertension. The scan format and recording process used in this patient differ from the others presented. The arrow indicates a structure in the posterior atrioventricular groove that is most likely either the coronary sinus or a large circumflex coronary artery. For details, see text.
For example, different scan programs may be written to maximize the system performance for use in pediatric, abdominal or cranial application.

Other planned additions to the system include an ECG display and timing reference marks. The incorporation of controls for time gain control ramp, video tape recorder and digital computer into one console will allow one man operation of the system. Ultimately, means for simultaneous M-mode recording of any selected line within the sector arc will be provided.

At the present time, a variety of clinical diagnoses may be based on the results of imaging with this new phased array system. Several examples of cardiac abnormalities are in-

FIGURE 6  Serial scans at different levels through the short axis of the left ventricle. In each, right is to the top of the scan. Panel A is at the level of the mitral orifice (position IV). Panel C is at the level of the papillary muscles (position V) and Panel E is at the level of the left ventricular apex. MVO = mitral valve orifice. See text for details.

FIGURE 7  Scan through the mitral valve orifice (position IV) in a patient with mitral stenosis. Note the narrowed mitral orifice. The arrow points to the thickened anterior mitral leaflet.

FIGURE 8  Paired diastolic (panel a) and systolic (panel b) scans through the short axis of the left ventricle (position V) of a patient with severe pulmonary hypertension. Note the flattened appearance of the left ventricle. Compare this appearance to the normal circular configuration of the ventricle in figure 6C.
cluded in this report and are seen in the narrowed mitral valve orifice of mitral stenosis (fig. 7), the enlarged right ventricle of right ventricular volume overload (fig. 4) and the striking features of the flail tricuspid leaflet (fig. 9). Anatomic features of abnormal left ventricular geometry are noted in the flattened left ventricle of a patient with severe pulmonary hypertension (fig. 8).

It is possible to see, therefore, that high quality two-dimensional images of cardiac structures are possible using a phased array transducer system. The system provides images of high line density, wide field of view and high resolution by electronically steering and focusing the sound beam. In the future it is possible that such a device will supply useful information concerning congenital lesions, normal and abnormal cardiac valve dynamics and altered left ventricular performance.

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