Clinical Results of Real-Time Ultrasonic Scanning of the Heart Using a Phased Array System

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This report describes the operating characteristics and initial clinical results of a new echocardiographic system that produces real-time, high resolution, cross-sectional images of the heart. This system relies upon phased-array principles to rapidly steer and focus the ultrasound beam through the cardiac structures under investigation. A hand-held, linear array of 24 transducers is manipulated on the patient's chest to direct the interrogating plane at various cardiac structures. Images of high line density are presented in selectable sector arcs to a maximum of 90 degrees. This imaging system has been used clinically in over 2,000 patients in the past two and one-half years. Its use in the detection of altered states of ventricular and valvular pathology has been described.

Real-time, two-dimensional cardiac imaging using phased-array principles differs from other ultrasonic methods because the sound beams are electronically, rather than mechanically, swept through a given cross-sectional field of view. This application of ultrasound relies upon basic principles concerning the summation of time-sequenced waves first described by the seventeenth century Dutch mathematician, Christian Huygens. Huygens' theory is fundamental to the explanation of wave propagation and forms the theoretical basis of many other similar imaging systems used in radar and sonar.

If an array of ultrasound transducers is arranged along a line and if these transducers are excited in rapid time sequence, then the wavelets emanating from the individual elements will add to produce a wavefront propagating at an angle to the line of the array itself. By changing the time sequence of the excitation pulses, the angle of wave propagation can be changed. This report describes the operation and application of a prototype focused, phased-array ultrasonic system that employs these principles to image moving cardiac structures in real-time [1,2].

METHODS

Developmental status and patients

All echocardiographic studies were performed using a real-time, two-dimensional imaging device, developed in the Duke University Department of Biomedical Engineering, that is presently undergoing clinical evaluation in the Duke University Department of Medicine. It is important to realize that this prototype imaging device is undergoing continual modifications in an effort to improve system performance, image quality and clinical capability.

Ultrasonic images presented in this manuscript are from among the first 1,000

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patients examined with this system. Patients underwent echocardiographic examination for a variety of clinical problems including rheumatic valvular, congenital, atherosclerotic and other forms of heart disease. During these phases of initial clinical trial, a variety of scan formats (e.g., varying sector arc width and line density), transducers and display and recording devices were utilized and thus account for variations in image quality presented.

**Transducer**

This system employs a hand-held transducer (presently 2.25 MHz) composed of 24 operating elements that measures 24 × 14 mm at the site of skin contact. The latter dimension corresponds to the height of each of the active elements. Images are displayed in a circular sector format (or sector arc) 40, 50, 60, or 90 degrees in azimuth (or width). Fig. 1 shows the arrangement of the elements along the transducer face and their relationship to the plane of a typical 60 degree sector arc. Depending upon the sector arc and range (18 cm maximum) selected, the line density and frame rate of the resultant image varies. When operating in the 90 degree sector arc, images are composed of 160 lines at a frame rate of 30 per second. When operating in the 60 degree sector arc, images are composed of 256 lines at a frame rate of 20 per second.

**System transmit and focus**

The manner in which the linear array is utilized to steer and focus the sound beam in a variety of directions is illustrated in Fig. 2. For the sake of simplicity, only a five element array is indicated. In Panel A, the electrical transmit pulses are seen to arrive from the left side. The top element is excited first and launches an acoustic wave into the tissues to the right of the array. An instant later, the second element is excited and, in turn, produces an acoustic wave. This process continues until the bottom element is finally excited. In the tissues, these five individually produced wavefronts will add, according to Huygens' principle, to produce an acoustic beam which corresponds in shape and direction (angle θ) to the propagation time sequence of the excitation pulses.

Panel B shows an extension of this method in order to achieve any given focus. Here, impulses are delivered to the individual elements by imposing a spherical timing relationship during the transmit mode. In the tissues, the transmitted wavefront is seen to be both steered and focused. To insure a relatively uniform focus throughout the field of view, five different transmit focal points (or depths) are utilized. In summary, all elements of the array are pulsed almost simultaneously to produce a focus along any individual scan line.

**System receive**

The method of receiving returning echoes is fundamentally different from that during transmission. In order to achieve uniform resolution throughout the field of view, the system also is able to focus at ten different points along one individual line during the receive mode by employing multiple analog delay lines. Thus, this system is focused during transmit and receive.

**System control**

This complicated sequence of dynamic focusing during sound transmission and reception is controlled by a PDP 11-20 computer. This device determines each aspect of the interrelationships between transmit and receive focusing.
PHASED ARRAY IMAGING

FIG. 1. The scan format. The cross-sectional image plane is parallel to the long axis of the linear array. Note the arrangement of elements on the transducer face plate.

A. Transmit steer

B. Transmit focus

FIG. 2. Transmit steer (Panel A) and focus (Panel B). Linear time and spherical time sequence of excitation pulses are seen to arrive from the left and then be propagated into the tissues on the right. See text for details.

System configuration

The overall system configuration is schematically diagramed in Fig. 3. Primary two-dimensional echocardiographic images in 10:1 gray scale are displayed in real-time on a Hewlett-Packard 1311-A display monitor. The recent addition of a simultaneous line selectable M-mode is displayed on a Hewlett-Packard 1335-A monitor. Silicone diode television cameras then view the display monitors and either one or both images are recorded on videotape (by means of a video mixer) for later playback and analysis. The system is equipped with a five step time-gain control ramp, switchable one centimeter range marks, overall gain and reject controls.

It is important to note that single frame scan images from the videotape recordings were made by means of a 35 mm photograph of the sector arc in the stop-frame
mode. As such, there is a loss of visual integration of motion that normally accompanies real-time playback. Moreover, there is a severe degradation in image quality caused by photographing a single frame image from the videotape recording because of the fact that an individual videotape frame represents the scan information collected in only 1/60th of a second. When operating in the 90 degree, 160 line format, therefore, each single frame video field shows only one-half (80 lines) of the information provided in the real-time scan.

Examination technique

Ultrasound examinations were performed with the patients in the supine or left lateral positions. The transducer is placed over an aquasonic gel interface to the left of the sternal border between the second and fifth 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. 4). Position I 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

Resolution test

Fig. 5 demonstrates the capabilities of this system for resolving four thin wire targets in range (Panel A) and in azimuth (Panel B). The range resolution is about 1.5 mm while azimuthal resolution throughout the field of view (3.5 to 18 cms) is 1.5 degrees. Resolution in the dimension perpendicular to the tomographic plane corresponds to values predicted for an unfocused slit aperture (6 db beam width is 8 mms at 110 mms range).

Cardiac imaging

Several stop-frame images from this system are presented. Fig. 6A shows a single frame image from an early scan performed through the long axis of the left ventricle (Position I). Cardiac structures are labelled in the schematic conception of the image in Fig. 6B. 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 pericardial effusion is seen behind the left ventricle.

Fig. 7 shows a still frame through the ventricular short axis at the level of the papillary muscles. Note the details of the internal left ventricular circumference that can be seen. Fig. 8 demonstrates the advantage of the 90 degree sector arc as the entire left ventricle is visualized in its long axis (Position I). Fig. 9 demonstrates the grey-scale capability of this imaging device as seen in a short axis view of the left ventricle and interventricular septum at the level of the papillary muscles (Position V).

Fig. 10 shows the details of left ventricular trabeculations that it is possible to see with this focused imaging device. Fig. 11 demonstrates the advantage of the mide sector arc in detecting substernal structures such as interatrial septum, right atrium, and tricuspid valve (Position II).

Unfortunately, the real-time operating capabilities of this device cannot be easily demonstrated within the constraints of the printed page.

DISCUSSION

The real-time, cross-sectional ultrasonic imaging system described in this report employs a unique, computer controlled, focusing system in an effort to improve image quality. This capability can be likened to an electronic lens where transmit
focus rapidly changes in range from one line to another. The electronic lens is active in the receive mode as the reflected sound information at a variety of predetermined ranges is also focused before the final image is displayed. All transducer elements take part in this process.

This computer controlled scan process not only provides unique flexibility in present system operation, but also permits ease in expansion for future capabilities. For example, when looking at intracranial structures, a lower frequency transducer is utilized. To optimize system performance, a new computer program must be entered.

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 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. Second, the wide field of view provided by the 90 degree sector occasionally allows for visualization of the entire left ventricle in long axis (Fig. 8). An added advantage of the wide sector arc is that it allows visualization of substernal structures such as tricuspid valve and the right atrium when the transducer is held adjacent to the sternum and angled in Position II (Fig. 11). Presently, this imaging system is not suitable for the examination of cardiac structures in neonates or small infants due to the limited near field of view in combination with compromised resolution and transducer artifact within the proximal 3.5 cms.
FIG. 6. Panel A shows a photo from a stop action videotape 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 the aortic valve 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; EN = endocardium; EP = epicardium; and P = pericardium. (Reproduced with permission from Circulation 53:262, 1976.)

FIG. 7. Ventricular short axis cross-section through the level of the papillary muscles (Position V). Note the definition of the endocardial surface visualized.

Since first clinically used in 1954 [3], time-motion echo-cardiography has justifiably enjoyed wide clinical application for the diagnosis of a variety of cardiac disorders [4]. Although clinical experience with real-time, two-dimensional echocardiography is still somewhat small, this new ultrasonic method provides spatial
FIG. 8. Stop-frame mid-diastolic image and schematic diagram through the long axis of the left ventricle in a 90 degree sector arc. There is mild ventricular dilatation. Virtually the entire left ventricle is seen from aortic root to apex. IVS = interventricular septum. Remainder of abbreviations are the same as in Fig. 6.

information concerning cardiac structures and, therefore, overcomes a primary limitation of M-mode imaging. This fact is of particular importance for the non-invasive evaluation of such things as left ventricular morphology and the detection of ventricular asynergy [5].

In more than two and one-half years of clinical use in this laboratory, over 2,000 patients have been examined with this new technique for a variety of clinical purposes. During this period of time, M-mode and two-dimensional echocardiography have been noted to work effectively together to expand the diagnostic capability of cardiac ultrasound for the non-invasive evaluation of rheumatic valvular heart disease [6], mitral prolapse [7], congenital heart disease [8], vegetative endocarditis [9,10], pericardial effusion and other cardiac disorders.

It is possible to see, therefore, that high quality, two-dimensional images of cardiac structures can be obtained using a phased-array transducer system. This system provides images of high line density, wide field of view and high resolution by electronically steering and focusing the sound beam. The inherent flexibility of this system provides a means for future system expansion and application.

The superior image quality and flexibility of this type of ultrasonic instrumentation
FIG. 9. Systolic stop-frame image and schematic diagram through the short axis of the left ventricle. A pericardial effusion is seen. Note the grey scale of the septal targets. Right ventricular trabeculations are seen. RV = right ventricular chamber. Remainder of abbreviations are the same as in Fig. 6.

FIG. 10. Stop-frame photo through the ventricular short axis showing details of various trabeculations on the endocardial surface of the ventricle.

results in improved sonic information for clinical purposes and, accordingly, enhances our diagnostic capabilities. It is the opinion of this author that future ultrasonic imaging of the heart will place heavy emphasis on phased array systems.
FIG. 11. Sequential diastolic (Panel A) and systolic (Panel B) stop-frame photos through the long axis of the tricuspid valve (Position II) in a normal patient. The wide secor arc provides access to substernal structures. Note that the right atrium is seen in the upper left portions of the scans while the inflow portions of the right ventricle are seen to the lower left. The atrial septum may be occasionally visualized in this view. SVC = superior vena cava; ATL = anterior tricuspid leaflet; RV = right ventricle; STL = septal tricuspid leaflet; IVS = interventricular septum; AML = anterior mitral leaflet; LV = left ventricular cavity; PML = posterior mitral leaflet; LA = left atrium; IAS = interatrial septum; RA = right atrium. (Reproduced with permission from Am J Card 38:502, 1976.)

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