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DYNAMIC INTRAESOPHAGEAL IMAGING OF THE HEART WITH ULTRASOUND

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Abstract

Real-time images of the heart from within the esophagus are produced by a new intraesophageal ultrasonic sector scanner. Sixty images per second are displayed on a gray scale CRT in real-time and recorded on standard videotape for review. By interactive positioning of the esophageal probe, heart ventricles, atria, and valves can be visualized and their dynamics can be studied. The esophageal probe comprises four 5 MHz PZT-5 piezoelements of 6.35 mm diameter, mounted on a shaft that rotates at 900 rpm. The piezoelements are pulsed at a 5 kHz rate and the echoes are processed electronically.

Key words: Cardiac; contrast; echocardiography; endoscopic ultrasound, esophageal; imaging; real-time; ultrasound.

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Introduction

Ultrasonic images and contrast studies of cardiac structures and their movements provide very useful diagnostic information. The efficacy of contrast studies in detection of cardiac abnormalities such as regurgitation and shunts has been reported for both M-mode and two-dimensional imaging [1-3]. However, there are a limited number of sites for imaging from the chest surface. Such limitations are mainly due to the interposition of the ribs and lungs, which are both highly reflective to ultrasound. Frazin [4] reported that satisfactory M-mode echoes cannot be obtained in only about 20 percent of the patients presented for examination. Sector scanning of the heart encounters the same limitations imposed by thoracic anatomy. Even more important, chest scanning falls short in providing images of many cardiac structures in even the best anatomical situations. The far wall and dorsal structures are examples. The intraesophageal approach, however, offers a virtually unrestricted ultrasonic view of the heart. Frazin [4] has already demonstrated the value of M-mode echocardiography from within the esophagus. Feasibility of sector scanning from the esophagus was demonstrated by Fearnot et al. [5]. Hisanaga et al. [6] have presented both M-mode and sector scan images using a transesophageal method. We believe that valuable ultrasonic contrast studies are possible with an esophageal sector scanner. This note describes a real-time ultrasonic scanner to be used in these studies, which acquires sixty 83 degree sector scans of the heart per second from within the esophagus.

Esophageal Probe

The esophageal probe consists of four 6.35 mm diameter, PZT-5 ceramic piezoelectric crystals, which are unfocused and resonate with a center frequency of 5 MHz. The beam width of the transducers is approximately 4.8 degrees as measured in the far field. Point targets either 1.5 mm apart in the radial direction or 3 mm apart in the angular direction can he resolved at 50 mm without image enhancement or filtering. Other measurements are also consistent with theoretical calculations. The shaft on which the crystals are mounted rotates at 900 rpm. Energy is coupled to and from each crystal through a slip-ring commutator. Electronic switching is arranged to pulse each transducer for one-quarter of a revolution with the four crystals being selected sequentially. In this way, four interlaced 83-line images are produced with each rotation of the shaft. The angular position of the rotating shaft is detected and communicated to the display by digital circuitry.

The transducers at the end of the probe are covered by a housing and rubber tip. The annular space between the rotating shaft and the housing is filled with fluid, introduced by a syringe (Figure 1). When in the esophagus, the rubber tip can he expanded to provide fluid coupling between the piezoelements and the esophageal wall. The overall diameter of the tip is 20 mm.

Electronic Circuitry

Control logic

The instantaneous rotational position of the probe shaft is detected optoelectronically. This position detector forms part of the display circuitry and motor speed control circuitry. The motor speed (900 rpm) is thereby phase-locked to a reference clock facilitating standard videotape recording. Pulsing and display circuitry are then synchronized to the instantaneous position of the transducer. The piezoelectric crystals are excited by the energy from a capacitor discharge at a 5 kHz rate. The resulting pulse has a 100 ns time constant.

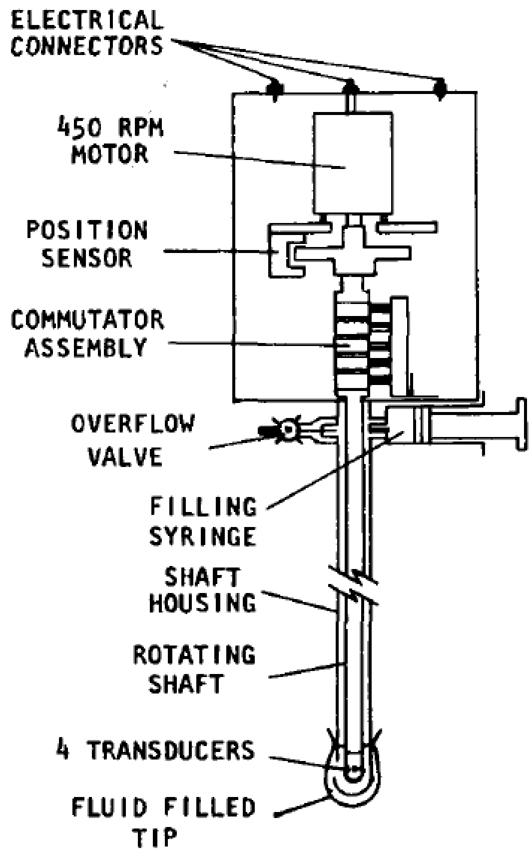

Figure 1. Schematic diagram of the esophageal probe.

Signal processing

The returning energy impinging on the crystals consists of echoes containing a wide band of frequencies. Echoes from only the pulsed crystal are processed for display. A low-noise, band-limited, range-gain amplifier compensates for echo attenuation through the tissues. A 60 dB gain range and 40 dB dynamic range allow flexibility in echo amplitudes. Piecewise gain control (range incremental control) allows both an approximation to exponential gain and highlighting of desired ranges. Echo amplitude detection, followed by lowpass filtering, provides an analog envelope signal, which brightens the display screen thereby creating a B-mode display.

Display

Information obtained by the probe, and processed by the electronic circuitry, may be displayed in a variety of modes, each with a specific diagnostic advantage. The device described in this note provides a choice of A-mode, M-mode, and B-mode sector scan presentation. To retain the motion information, as well as the still image, the real-time image in formation was made compatible with any standard videotape recorder. Sufficient information can be retained on a standard videotape cassette to enable display of the information in A-mode, M-mode, or sector scan.

To create the sector scan, the vertical and horizontal amplifiers of the display scope are driven with a ramp-wave, digitally modulated by sine and cosine signals. The lines of the display are generated each 185 μs so that one line is generate for each degree of transducer rotation. With interlacing, a line appears each quarter degree. The intensity of points along these lines is determined by the reflected echo amplitudes. This line density shows few radial-line artifacts on a 10 cm oscilloscope screen and therefore provides a clear image.

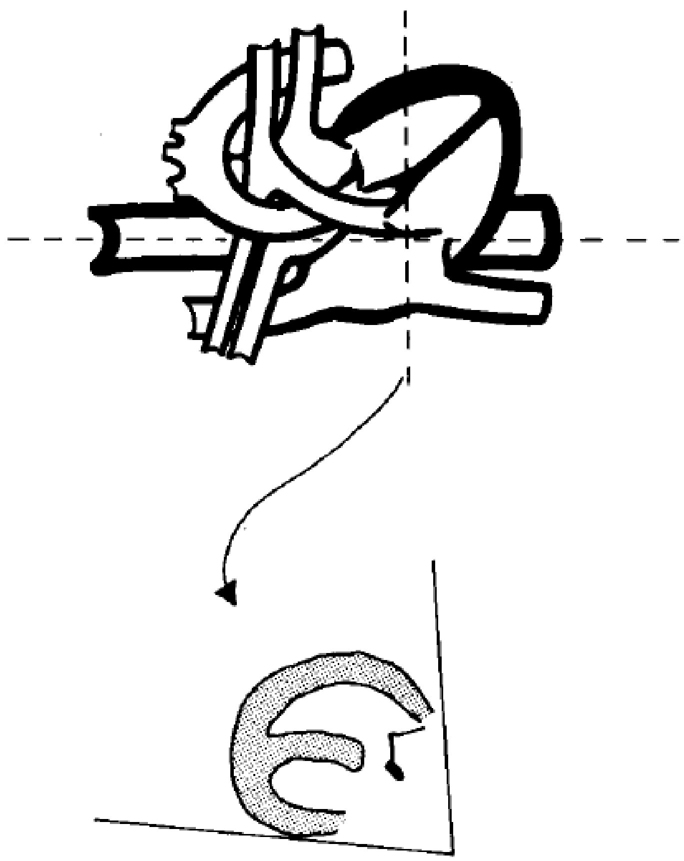

Figure 2. Orientation of the image produced by the esophageal sector scanner. The image is a cross section of the cardiac structures lying in the transverse plane of the thorax with the origin of the sector representing the esophagus.

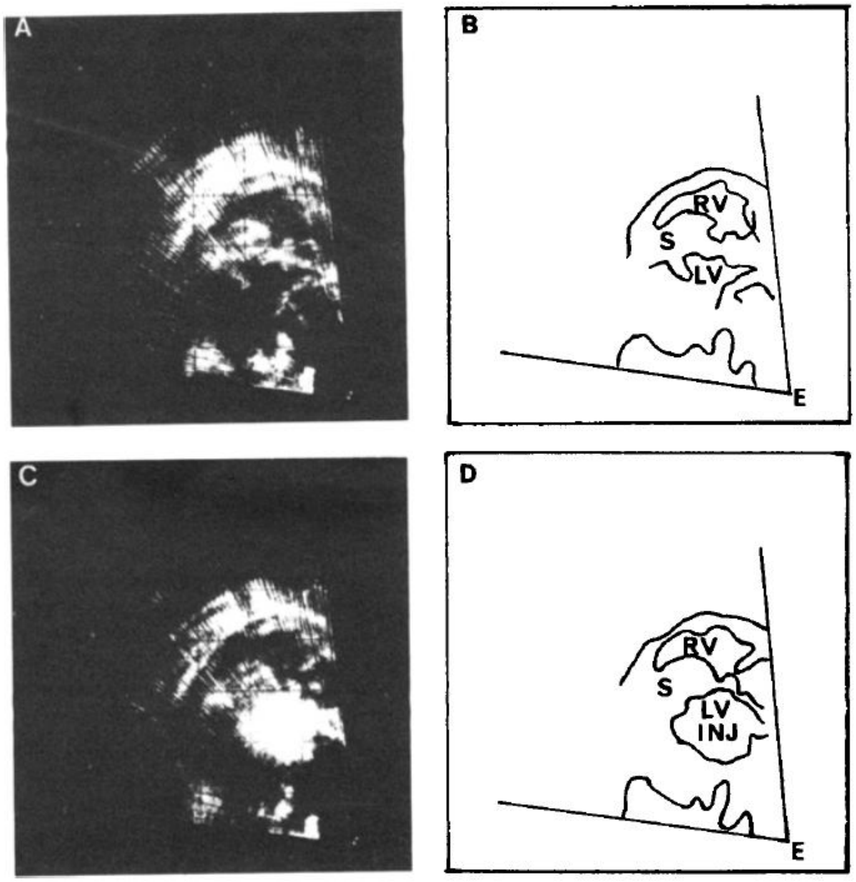

Figure 3. Sector scan images of the heart from within the esophagus. (A) The right and left ventricles appear as dark cavities surrounded by the left and right ventricular free walls and septum as indicated by the sketch (B). The origin of each sector coincides with the esophagus. Certain intraventricular structures are also evident in the image. (C) Right and left ventricles; the free walls and the septum are clearly visible as indicated by the sketch. (D) Verification of the left ventricular cavity by injection of cold saline resulted in the bright cloud of contrast within the left ventricular cavity (LV INJ).

Results

Figure 2 is an orientation to the image produced by this device. The image appears as a transverse cross section of the thorax being viewed from the head. The lower right corner of the scan coincides with the esophagus, which is dorsal to most cardiac structures. Figure 3 includes two photographs representative of esophageal sector scans obtained in an anesthetized, supine dog. The probe was advanced to the level of the fifth rib, where cardiac structures became most apparent. In each image, the ventricular walls and interventricular septum are clearly visible. Intraventricular and valvular structures are also evident. These photographs were taken before and after left ventricular injection of 10 ^{o}C saline through a number 7 French catheter advanced into the left ventricle from the carotid artery. Similar contrast studies were carried out for the right ventricle to verify structures. Although many structures could be clearly verified and visualized while examining the dynamic image, structures such as valves are very difficult to identify in the still image, demonstrating the value of videotape storage of the dynamic image. In the real-time image, these cardiac structures are clearly visible and move with each systole and diastole. With a stop-frame accessory, both amplitude and velocity can be measured.

Discussion

The esophageal sector scanner provides a new dimension in cardiac imaging. The outlines and motion of valves, ventricles, atria, and great vessels can be clearly identified by choosing the correct orientation and level within the esophagus. The feasibility of valuable contrast studies and cardiac kinesiology from this new sight has been demonstrated with the esophageal scanner. Because the images are produced in real-time, interactive positioning of the probe is possible. The compatibility of the scan with standard videocassette recorders allowed efficient storage of the images for reviewing. Replaying of the examination permitted careful study of the dynamics of structures such as the aortic and tricuspid valves and ventricular walls. As promising as this study was, some possible improvements in the scanning system that would facilitate more useful images and a more practical instrument were identified. Since the axis of the heart is oblique to the axis of the esophagus and the imaging plane is at right angles to the esophageal probe, the resulting oblique sections of the heart are anatomically less familiar than standard transverse sections. Some echo amplitudes may also be reduced when tissue-fluid interfaces are oblique to the ultrasonic beam. For these reasons, examination of the heart at angles oblique to the esophagus is desirable. We believe that both the long and short axes of the heart are obtainable from within the esophagus. Future modifications will be in this direction.

Since the esophageal probe was designed for feasibility studies in animals, the 20 mm diameter was not a major disadvantage. The probe easily passed down the esophagus of an anesthetized dog. However, now that feasibility has been demonstrated, it is clear that the next generation probe should be no more than 10 mm in diameter and must be flexible. The optoelectronic sensing of transducer position will allow position sensing at the tip of a flexible probe. Research is now underway to develop a thin esophageal scanner able to image in a plane oblique to the esophagus.

At present, interest in cardiac imaging from within the esophagus is increasing and other devices for esophageal imaging are being developed. In the very early days of ultrasonic imaging, interestin imaging from within the esophagus was noted. A multi-purpose, rotatable scanner for this purpose was described by Ebina et al. [7]. Eggleton et al. [8] described a rotating multi-element transducer in a semi-flexible tube for esophageal imaging. The image plane was at right angles to the axis of the probe. Fearnot et al. [5] reported a scanner that produced thirty 90° images per second. More recently, Hisanaga et al. [6] developed a similar probe that imaged in a plane perpendicular to the esophagus and rotated at various speeds from 4-15 rpm. Use of a linear array transducer in the esophagus has also been reported [9].

From our study and from these other reports, special technical features required for contrast studies and dynamic imaging in the esophagus are evident. For example, as with other ultrasonic imaging systems, it is necessary to be able to interact with the imagery as it is acquired in real time and provide a means of long term storage for re-examination. Because of the oblique position of the heart relative to the esophagus, it is desirable to be able to adjust the plane of imaging with respect to the axis of the esophageal probe. With improvements in these areas, esophageal imaging could provide significant advances in the detection of valvular abnormalities and dyskinesia due to myocardial infarction. New contrast methods using esophageal imaging should provide better visualization of many cardiac structures.

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