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Real-Time 3D Ultrasound: A New Look at the Heart

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ABSTRACT

Matrix array ultrasound is a medical imaging modality in which a 3D volume is scanned electronically without physically moving the transducer, permitting rapid continuous 3D scanning of the heart. Unlike reconstructive 3D ultrasound, which relies on physically moving a linear array and acquires data during multiple cardiac cycles gated to the ECG, matrix array ultrasound has no moving parts, resulting in a scan rate rapid enough (22 frames/second) to smoothly sample heart motion within a single cardiac cycle. Therefore, these cardiac studies have been described as real time, and the modality itself has been labeled Real-Time 3D (RT3D) ultrasound. We review the first application of matrix array ultrasound to *in vivo* cardiac imaging of normal volunteers, describing methods of displaying the data during the scan, as well as afterwards on a graphics replay station. We conclude that by introducing the capability of real-time 3D cardiac imaging, matrix array ultrasound provides an important new clinical tool.

INTRODUCTION

At Duke University we have developed an imaging technology known as Real Time 3D (RT3D) ultrasound, based on a matrix array transducer that scans a 3D volume electronically.[(1–5)] Replacing the single row of elements found in conventional linear (1D) transducers (see Fig. 1A), the elements in a matrix array transducer are arranged in a two-dimensional grid (see Fig. 1B). As with the linear array, the direction in which the matrix array transmits and receives ultrasound energy is controlled by timing individual transducer elements during transmission and reception of the ultrasound. With a linear array, only the direction within a slice, the so-called azimuth, can be controlled, whereas a matrix array offers steering in both the beam's azimuth and elevation, permitting interrogation of an entire pyramid-shaped volume. Using the prototype of matrix-array ultrasound machine known as "T4" (see Fig. 2), we have conducted *in vivo* studies and explored methods of displaying the volumetric data.

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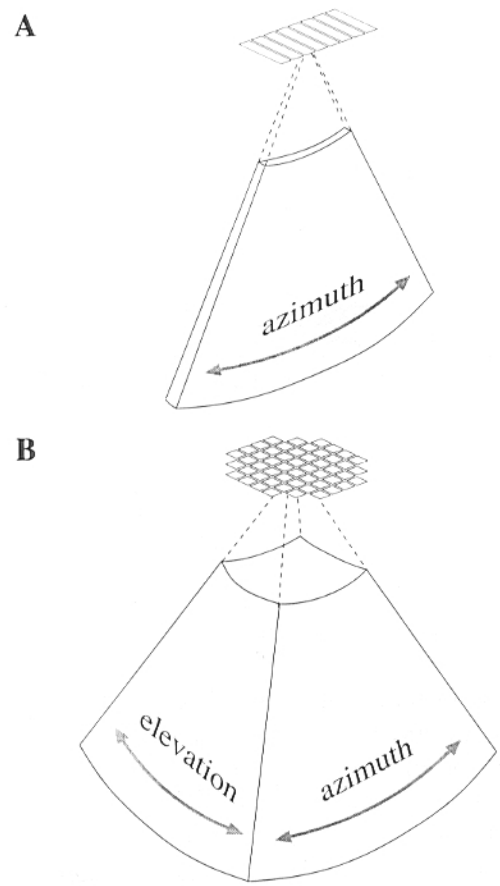

FIG. 1. (**A**) A linear (1D) array can focus within a single slice, controlling the azimuth of the beam by varying the phase between transducer elements. (**B**) A matrix array adds another dimension, permitting control of the beam's elevation and allowing the scanner to focus anywhere within the pyramid-shaped volume.

Scan versus view

In the routine description of medical images, clinicians follow standard conventions as a matter of expedience and to reduce ambiguities in their reports. The accepted terminology develops only through practice and differs with each imaging modality. Such a standard has yet to evolve for 3D ultrasound but we find it convenient to differentiate between the *scan* and the *view*. The reason for this distinction is that the anatomical content of a 3D ultrasound image is determined by two separate factors: (1) the transducer location with respect to the patient, and (2) the slice location within the data pyramid.

In this article we use *scan* to denote transducer location. As in conventional echocardiography, a parasternal scan means the transducer is aimed between the ribs adjacent to the sternum, and an apical scan means the transducer is positioned below the ribs, pointing upwards at the apex of the heart. The particular scan is established when the data is collected and cannot be altered thereafter.

We use *view* to denote which slice (or sub-volume) within the data pyramid is displayed. The view can be determined after the data are captured or by adjusting the display parameters during the scan without moving the transducer. Possible views include the basic slice orientation: B-mode, C-mode, and inclined C-mode (I-mode). Further categorization may relate the view to the underlying anatomy, such as *4-chamber, short-axis*, or *long-axis*, terms already familiar from 2D ultrasound. With volumetric displays, orientation with respect to the viewer must also be specified, for example, to differentiate between *short axis from apex and short axis toward apex.*

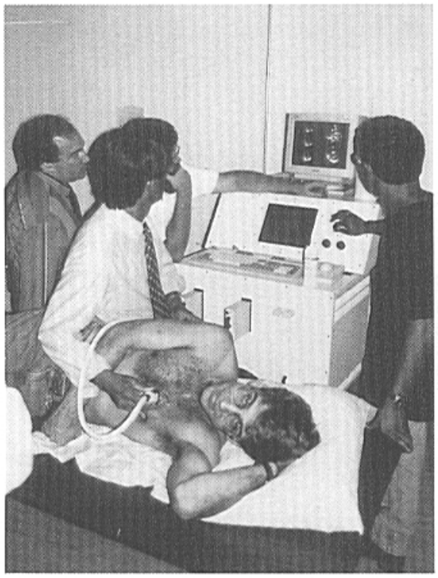

FIG. 2. A parasternal scan in progress using the T4 scanner.

MATERIALS AND METHODS

T4 scanner

The T4 ultrasound scanner contains 256 independent transmit channels and 256 independent receive channels. Transducer elements are cut in a matrix with each element being square and approximately 300 μm on a side. A typical transducer array is circular with a diameter of approximately 25 mm and an active aperture of 15 cm, operating at a frequency between 2.0 and 3.5 MHz. Because of 16:1 parallel processing,[1] T4 can accomplish a typical cardiac scan of a 13 cm deep, $64° \times 64°$ pyramid-shaped volume containing 4,096 receive paths at a rate of 22 volumes per second. The scan rate depends on scan depth, with scan rates of 40 volumes per second possible at 6 cm, but only 14 volumes per second at 20 cm.

An important feature of scanning with a matrix array is that, unlike scanning with a conventional linear array, dynamic focusing is possible in both lateral (cross-beam) dimensions. Therefore, the beam pattern from the matrix array is circularly symmetric in the cross-beam dimensions (see Fig. 3B). Rectangular apertures in linear arrays result in beam patterns that differ in the two lateral dimensions (see Fig. 3A), with a typical resolution of $6 \times 3 \times 2$ mm (elevation, azimuth, range). The measured volume resolution of the T4 scanner is $3 \times 3 \times 2$ mm, at a range of 70 mm with a 2.5 MHz transducer, which is small enough to resolve such relatively thin structures as valve leaflets and endocardium.

On-line display and capture

The primary display for the T4 system is a 60 Hz 640×480 pixel monitor receiving the output of the 3D scan conversion system in real time. The display may be configured to include up to 16 simultaneous slices through the 3D data set, although the standard configuration is five slices as shown in Figure 4 (an apical scan). The two B-mode images on the right are physically perpendicular within the heart, as shown in Figure 5A. The top B-mode image in Figure 4 is a 4-chamber view showing a slice through two ventricles, two atria, and the valves between them. The bottom B-mode image is a 2-chamber view. These views are familiar to cardiologists, who presently achieve them sequentially by rotating the transducer. With matrix array ultrasound, they are simultaneous views from the same 3D scan. The two B-mode slices may be swept independently through the data pyramid.

Displayed on the left of Figure 4 are three C-mode slices, which are image planes parallel to the face of the transducer. These C-mode slices show cross sections of the left and right ventricles displaying their con-