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ORGAN VOLUME DETERMINATION BY ULTRASONIC THREE-DIMENSIONAL RECONSTRUCTION

"Data-driven" system

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A computer system has been developed for obtaining three dimensional reconstructions of organs using ultrasound. A series of real time two dimensional ultrasonic slices are acquired throughout the organ. A special acoustic position locating system allows scans to be related to each other in three dimensions. A light pen is used to outline the border of the organ on each scan. The position and light pen information is combined to produce a 3D reconstruction as a series of slices through the organ surface. Volume is found by a process of linear interpolation. Perspective displays of the organ are obtained with a set of 3D line drawing routines. Example displays and volume results are presented.

Introduction

The use of real time ultrasound in medicine has increased over the past few years largely because of the non-invasive, apparently harmless nature of sound as an imaging medium. Although most clinical uses of ultrasound are still qualitative there are now several areas where quantitative measurements are being made on the ultrasound image. For example, left ventricular volume, which is an important indicator of heart function, has been estimated by taking a two dimensional ultrasonic slice through the ventricle (1). The endocardial border is outlined on the image, and volume is computed by assuming an ellipsoidal shape. Fetal weight, an important indicator of well being _in utero_, has been estimated by combining several length and circumference measurements in multiple regressions against birthweight (2). However, ultrasonic left ventricular volumes or fetal weight estimates have not been very accurate when compared with presumed gold standards. The most likely explanation for this inaccuracy is the fact that organs are complicated three-dimensional structures which are not easily approximated by simple shapes. The most accurate volumes should come from information obtained throughout the organ surface. Accurate fetal weights should also come from volumes since there is a close relationship between fetal weight and volume (3). Because of the relative ease with which the ultrasound transducer can be manipulated it is generally simple to acquire images from all portions of the organ. However, since current generation ultrasound instruments display only a two dimensional slice through the organ there is no way to relate slices obtained from different orientations.

A system, called SCANR, has been developed at Stanford for utilizing three dimensional information to find organ volumes. The system is based on a similar system originally developed at the University of Washington (4). A special three dimensional acoustic position locating system is attached to a commercially available ultrasound scan head. The locator allows arbitrarily oriented ultrasound slices to be related to each other in three dimensions. The organ is imaged from a large number of orientations so as to acquire data from all portions of the organ surface. A light pen is used to outline the organ border on each scan. The locator plus light pen information is combined to produce a reconstruction of the organ surface as a series of slices. Volume is found by a linear interpolation process. The reconstructions and interpolated scans may be displayed in perspective on a graphics terminal. The following paragraphs describe the system in more detail, and the results of some volume calculations.

System Description

Data Acquisition System. A commercially available Toshiba 3.5 Mhz linear array scanner is used to acquire the ultrasound images. The position locator, which was designed and built by Moritz at the University of Washington, (5), is a modification of the GRAFPEN two dimensional sonic digitizer. A set of three small hemispherical microphones are arranged at right angles to each other to form a three dimensional microphone coordinate system. The microphones are placed at a fixed location over the patient. A flat plexiglass plate containing three small spark gaps is mounted on the ultrasound scan head. When a footswitch is pressed each spark gap is fired in turn by a dedicated microprocessor. The transit time of the acoustic shock wave produced by the spark is measured between the spark gap and each of the microphones. Given the speed of sound in air the distance between the spark gap and each microphone is determined, from which the three dimensional microphone coordinates of the spark gap can be calculated. Since three points are required to define a plane the 3D microphone coordinates of the three spark gaps, which are fixed in a known way with respect to the scan plane, are enough to completely define the position and orientation of the scan plane in space.

The development of a reconstruction and volume takes place in three steps which are controlled by computer programs named as follows: PAS1, when ultrasound scans and position information are acquired from the patient; PAS2, when previously acquired scans are outlined with a light pen; and PAS3, when the reconstructions and volumes are calculated. PAS1 and PAS2 run on another microprocessor (separate from the locator microprocessor), while PAS3 runs on a PDP-10 timesharing computer. The reason for separating the steps in this way was to make the actual patient exam time as short as possible.

During PAS1, the patient exam, ultrasound slices are acquired throughout the organ being imaged. For each slice the locator footswitch is pressed, causing a description of the current scan plane position to be written on a floppy disk file. At the same time the video output of the scanner is fed through a 256 x 256 overlay memory so that a scan number may be superimposed on the image. In this way the proper correspondence between positions and scans is maintained. The combined scan number and ultrasound image is recorded on a video tape recorder.

During PAS2, data entry, scans are retrieved from the video tape recorder via a video disk (to allow adequate still frames to be obtained). A light pen is used to outline the organ boundaries on each scan; the resulting XY light pen coordinates are stored on the same floppy disk file that contains the 3D position information for the given scan.

During PAS3, data analysis, the floppy disk file is sent to the PDP-10 where the reconstructions and volumes are calculated. A Calcomp pen plotter associated with the PDP-10 is used to produce perspective displays of the organ.

Reconstruction and Volume Calculations. The data sent to the PDP-10 consists of a series of ultrasound slices, each represented by a set of vectors describing the position of the scan plane with respect to the microphones, and a list of two dimensional XY light pen coordinates describing the location of the organ border on the slice. By utilizing the position vectors and known relationships between the scan plane and the spark array, a series of coordinate transformations are carried out. The result is that the original XY coordinates for each slice are converted to three dimensional microphone coordinates. Since the microphones remained fixed throughout the patient exam these 3D coordinates provide the desired means for relating individual slices to each other.

Given such a set of slices, represented as 3D microphone coordinates of points on the surface of the organ, volume is found by a process of double linear interpolation. During the patient exam the approximate ends of the organ must be indicated on at least one scan each. The 3D coordinates of these points are used to establish a long axis through the organ, from which an organ coordinate system is established. A plane is passed through this axis and is rotated in increments of 15 degrees around it. At each increment the intersection points between the plane and the ultrasound slice points are found by linear interpolation. These points are sorted into a closed outline, called a longitudinal interpolated scan. The complete set of 12 longitudinal interpolated scans look like the slices of an orange. A second interpolation is then done on these longitudinal interpolated scans by a series of 21 planes perpendicular to the long axis. The resulting parallel cross sectional scans are summed by Simpson's rule in order to find volume. The intersection points found in forming the interpolated scans must be sorted because the ultrasound slices were acquired in a completely arbitrary fashion. The current sorting algorithm simply looks for nearest neighbors. Since this simple heuristic often fails for complicated shapes the sorting process is interactive and therefore time consuming (about 15 minutes per volume). The advantage of this particular volume technique, however, is that no <u>a priori</u> shape is assumed for the organ (such as an ellipsoid), thereby allowing more accurate volumes.

Perspective displays of the original ultrasound slices and the interpolated scans are made by means of a set of simple three dimensional line drawing routines. Rather than display the organ reconstruction in terms of the microphone coordinate system, which has no obvious relationship to the patient, the reconstruction is displayed in terms of a "patient" coordinate system. This coordinate system is established at the beginning of the exam by determining the three dimensional microphone coordinates of three anatomic landmarks on the patient. For fetal imaging these landmarks are the xiphoid, the pubic symphysis, and the left hip. Perspective displays shown in terms of the patient coordinate system are more easily interpreted in relation to other organs in the body.

Evaluations

<u>In vitro Volumes</u> A series of volumes were computed on progressively more irregular objects (6). Thirty volume trials on 10 water filled balloons gave 27 out of 30 calculations within 1.8 percent of true volume. Eighteen trials on 6 kidneys gave 17 out of 18 calculations within 5.1 percent of true volume. Fifteen trials on 5 latex molds of the human left ventricle gave 13 out of 15 calculations within -5.9 percent of true volume. Figure 1 is a perspective display of one of the molds. The left portion shows the original ultrasound slices; the right portion shows the interpolated scans used to find volume.

<u>In Vitro Fetal Weights</u> Three dimensional head and trunk reconstructions were obtained on a series of 25 dead neonates immersed in a water bath (3). Calculated head plus trunk volume was compared with measured weight in a multiple regression. The correlation between measured weight and calculated head plus trunk volume was r=0.985, with a standard error of 190 grams (weight range 364 to 3650 grams).

<u>In Utero Fetal Weights</u> Three dimensional head and trunk reconstructions were obtained on a series of 41 live term fetuses <u>in utero</u> (7). The measurements were made within 48 hours of delivery. Figure 2 shows one of these reconstructions displayed in terms of the patient coordinate system: the origin is the pubic symphysis, the point "C" is the left hip bone (left anterior iliac spine).

Calculated head and trunk volumes were compared with measured birthweight in a multiple regression. The correlation between measured weight and calculated head and trunk volumes was r=0.904, with a standard error of 266 grams (weight range 1985 to 4734 grams).

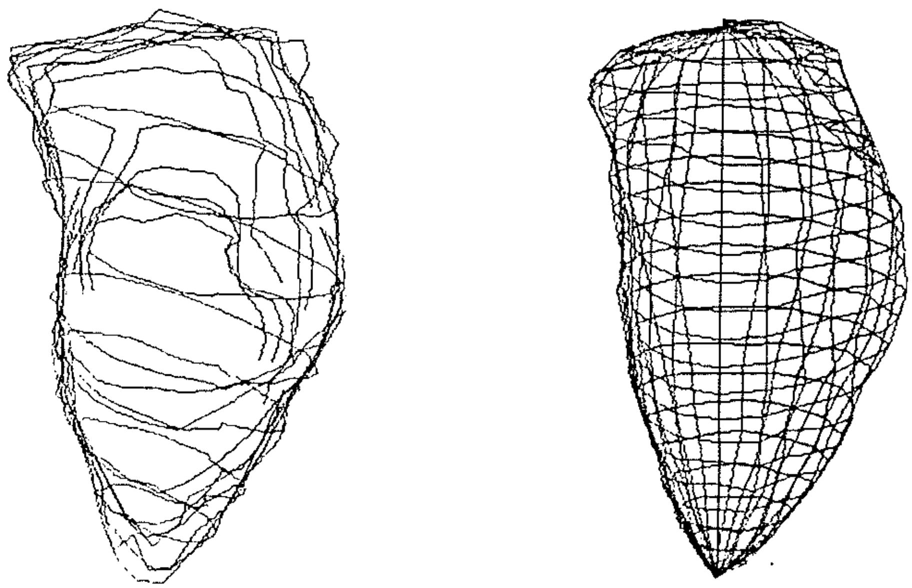

Figure 1: Latex mold of human left ventricle

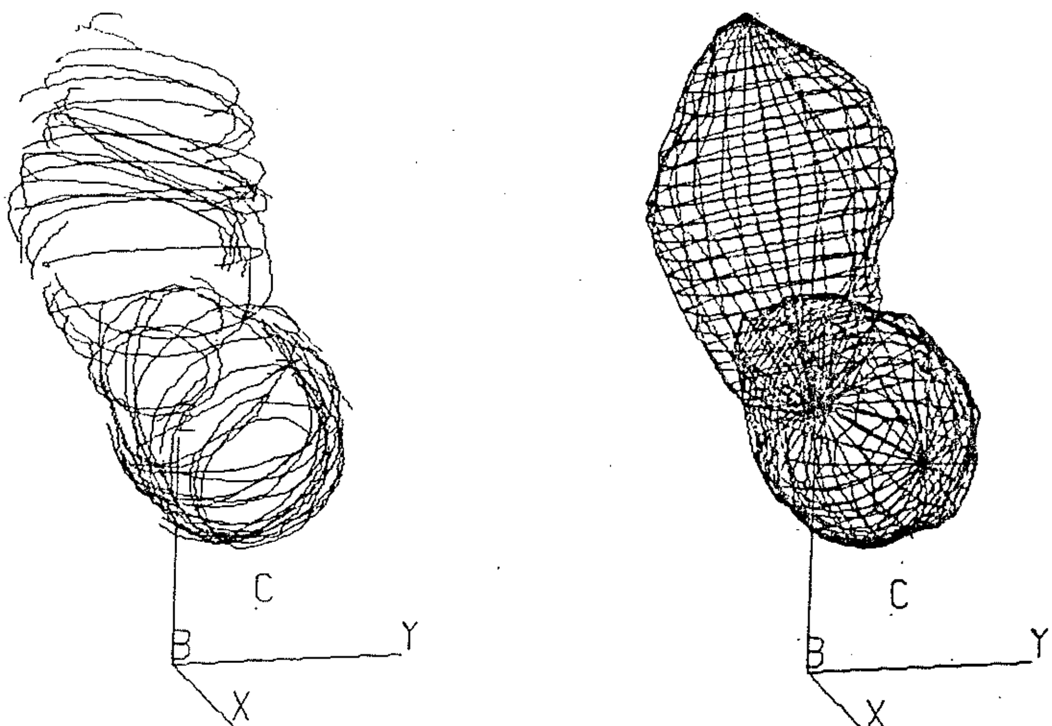

Figure 2: Human fetal head and trunk, In Utero

Discussion

The in vitro evaluations have shown that quite accurate volumes are obtainable with this technique. Fetal weight estimation in utero was not as accurate, which might be expected in the clinical situation where movement and poorer quality images occur. Also, in estimating weight we were only measuring head and trunk volume without including the limbs.

The technique has several limitations; for example, motion must be minimized, the entire organ surface must be visible, and the procedure is very time consuming (approximately 45 minutes per reconstruction). These limitations will necessitate further work before the system is ready for clinical use. Nevertheless, the initial evaluations have shown that the addition of computer processing to commercial ultrasound instruments can provide diagnostic information that was not available previously.

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