QUANTITATIVE ANALYSIS OF THREE-DIMENSIONAL IMAGES OF THE LEFT VENTRICLE GENERATED WITH THE DSR

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Abstract

Accurate description of anatomy and function of the heart requires the ability to measure a three-dimensional object changing shape in time. The Dynamic Spatial Reconstructor (DSR) is an imaging system capable of making these measurements. DSR data are immense in quantity, and require powerful digital computing systems for generating and manipulating images. An example is presented where the DSR system is used to quantitate local canine myocardial function in vivo. Application of this method could result in a more comprehensive and more accurate understanding of function in the healthy and pathologic heart.

Introduction

With the availability of the DSR in the late 1970s, we have been able to non-invasively measure three-dimensional cardiac structure and function in vivo with increased accuracy. This increased accuracy results from extension of measurement capability from two dimensions to three dimensions. The purpose of this paper is to describe through example our initial attempts at quantification of cardiovascular mechanical function by 3-D image analysis.

The DSR System

We shall first discuss briefly the operation of the DSR (Figure 1) as a three-dimensional imaging device. The reader is referred to the references1-2 for a more detailed description of DSR operation.

The DSR is a high-speed, synchronous, x-ray volume imaging system based upon computerized axial tomographic (CAT) principles. It has 14 imaging chains, each consisting of a pulsed, cone-beam x-ray source, a fluorescent screen mounted opposite the x-ray source on a rotating gantry and 14 isocon video cameras, also mounted on the gantry. Each camera images a segment of the fluorescent screen. The gantry rotates axially about the patient at a rate of 1 revolution every 4 seconds. Each fluorescent screen image is thus a rotating two-dimensional projection image of the subject under study. These video projection images are stored in multiplexed form on analog stop-action magnetic video discs. Sixty multiplexed video fields from each 14 imaging chains are stored each second. Thus, 14 simultaneous angles of view of the subject are recorded each .0167 sec. The volume imaged by the DSR is cylindrically shaped and measures 22-39 cm in transaxial (usually transverse) diameter by 22 cm in axial (usually cephalocaudal) length. This volume is thus represented as a series of sequential, closely spaced (equivalent to 1.8 mm apart) analog video lines recorded through time. Following completion of a DSR scan (average ~6 seconds), the projection images are digitized line-by-line from video disc and processed with a filtered back projection reconstruction algorithm3. This yields roughly 128 sequential transverse images in space (each 128 x 128 pixels) which together completely represent the aforementioned volume. Each small volume image element is called a voxel, and all voxels (128 x 128 x 128 = 2.097 x 109 total) are called a volume image (see Figure 2).
A three-dimensional volume image is created by stacking serial two-dimensional transverse images. Arbitrary plane sections through any desired structure are made by selecting voxels which lie on a plane intersecting the cubic volume. (From Ritman, E. L., R. A. Robb, and E. R. Wood: Synchronous volumetric imaging for non-invasive vivisection of cardiovascular and respiratory dynamics: Evolution and current perspectives. Mayo Textbook of Cardiology (In Press). With permission.)

**DSR Data Characteristics**

It is helpful to understand that each transverse image of a volume is equivalent to a single transverse image generated by a commercial CAT scanner. The difference between the DSR and the commercial CAT scanner is that the DSR generates data for roughly 128 synchronous slices every 0.0167 sec whereas the CAT scanner generates a single slice in about 2-4 seconds. That the volume of DSR data is immense can be seen by the fact that $128 \times 128 \times 128$ voxels x 5 sec or about 627 million 16-bit digital values, each corresponding to the time varying x-ray density of a small (e.g., 1 mm$^3$) volume in space.

The DSR scanner enables us to accurately study the structure and function of an irregular, moving three-dimensional object such as the heart. A powerful digital computer system is required to manipulate the reconstructed data within a reasonable time period. Initial studies of the cardiovascular-respiratory system using the DSR have generated physiologically useful images, and quantitative measurements in three dimensions made with these images are repeatable and accurate to within at least 5%.

**Example - Left Ventricular Wall Thickening Dynamics**

An area of great clinical interest is that of quantitating regional or local ventricular function. Because of the left ventricle's complex shape (see Figure 3), approximations presently made assume the ventricle to be conical, cylindrical or ellipsoidal. Although these assumptions have some merit in estimating global ventricular volumes, they cannot provide surface shape information that was not measured primarily. This limitation is especially applicable in evaluating regional ventricular function or local myocardial performance.

One method of estimating regional myocardial function is by measuring wall thickening from diastole to systole, and the time rate of thickening in a functioning ventricle. Healthy heart muscle shortens during systolic contraction and the effective volume contained by the ventricular cavity decreases by about 50-60%. Cardiac muscle fibers shorten and bring about muscle wall thickening for the following reason. Heart muscle mass is relatively constant (actually, there is a small change in volume), and muscle density is constant since much of it is water. Muscle volume should then be relatively constant through the cardiac cycle as well. We can express this conservation of mass in the following closed surface integral over, for example, the left ventricle:

$$m = \oint T(r,\theta,\phi,t) \cdot \rho \, ds$$

where: $ds$ = differential surface area element $r,\theta,\phi$ = generalized spherical spatial coordinates $t$ = time $T$ = muscle thickness function $\rho$ = density of muscle $m$ = ventricular mass

We know that during contraction ventricular cavity volume decreases so that $\oint ds$, or ventricular endocardial surface area, is not constant.
Thus, $T(r, \theta, \phi, t)$ must be a time varying function in order to maintain a constant in time. Use of this concept has shown that the spatial thickness function $T$, and better yet its time derivative $\partial T/\partial t$ is a sensitive indicator of local myocardial contraction. Regions of ischemic myocardium show both lower percent thickening as well as lower rates of systolic thickening. The concept of regional wall thickening is comparatively simple, but when biplane angiographic or echocardiographic images are used, a limited amount of myocardium is accessible for evaluation of wall dynamics. Furthermore, measurements are not synchronous for different regions imaged at different angles of view. Although 3-D imaging such as with the DSR overcomes this limitation, measurement of 3-D geometry remains a complex task.

It must be emphasized that simultaneous measurement of a ventricular parameter such as regional wall thickening over the entire surface provides information, for example, on how function in one region of the ventricle affects another, especially under acute, transient conditions. Symmetry assumptions regarding the ventricle are untenable when it is precisely the asymmetric properties of this surface in which we are interested. We believe description of the contracting ventricle can be achieved by a spatial vector point function in time.

By using DSR generated volume images throughout a cardiac cycle, it is possible to measure the local wall thickness over the entire extent of the ventricle. In the studies to be discussed, radiopaque contrast agent was simultaneously injected into the right and left atria of a normal dog during a DSR scan. After reconstruction, a time sequence of digital volume images was stored in an analysis computer. A left ventricular long axis was defined as a line from apex to aortic root. The analysis computer, via an "arbitrary sections program" was instructed to make thick (.5 cm) plane sections from each volume image perpendicular to the long axis. This is done by selecting voxels lying in sequential planes normal to the axis and assembling them into a stack of serial spatial sections. An example of sequential spatial sections at a given point in time is shown for a normal dog heart in Figure 4. These are short axis sections and a typical sequence at a given plane in space through time is shown in Figure 5, with time intervals of .067 sec between images. From this series it is clear that one may measure wall thickness changes through time around the entire myocardial left ventricular circumference in any chosen section. By doing the same for all spatial short axis left ventricular views, the entire wall thickening function $T$ for the left ventricle has been defined. It is likely that error occurs in thickness measurement as the wall deviates from parallel to the long axis. This error is generally proportional to the Secant of the deviation angle. However, the error is generally not a factor unless the wall translates in and out of the plane under consideration.

In practice, thickness measurements are calculated digitally from cursor pointing routines guided manually, at intervals of 45-60° about the left ventricular long axis. Local rates of thickening may then be easily calculated for the entire surface area of left ventricle.

Data presentation for thickening over the endocardial surface is done in two-dimensional video format as shown in Figure 6 for the normal dog example of Figures 4 and 5. It is important to realize that this method of presentation suffers from the problem of forcing a curved surface into a flat plane. This is similar to the cartographer's problem of projecting the earth's curved surface onto a flat map.

Distance along the left ventricular long axis is represented on the abcissa, circumference of the ventricle at its various parts along the ordinate,
Heart muscle. The horizontal axis is distance derived from circumferential wall measurement in minimum of the left ventricle. Intensity is the scaled value to the clinician or researcher studying ventricular function, for instance, in correlating coronary artery anatomy with the epicardial or endocardial surface, but in general this option is not available in a clinical setting.

**Conclusion**

Many of the simplifying assumptions used for analyzing fluoroscopic and echocardiographic (2-D) images must be discarded if 3-D image data is to be fully exploited for greater accuracy. This paper explores an approach to describing complex dynamic wall structure and behavior of the left ventricle. This approach may be useful in delineating regions of abnormal myocardial function from regions of abnormal myocardial wall structure.

**Acknowledgements**

The authors wish to acknowledge the expert help of Harje Fynbo, Steve Richardson, and Jim Hanson in the preparation of this manuscript.

This work was supported in part by Research Grants HL-04664 and HL-28473 from the National Institutes of Health.

**References**


