Assessment of Ventricular Wall Thickness in Vivo by Computed Transmission Tomography

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SUMMARY The present study was aimed at investigating the potential of computed transmission tomography (CT) scanning for quantitative assessment of interventricular septal wall thickness in living dogs. Seven normal beagles and seven litter mates with left ventricular hypertrophy were scanned in order to determine the sensitivity of the method. Left ventricular hypertrophy was created by banding the ascending aorta when the dogs were 6–8 weeks old. The operated dogs were followed, along with their normal litter mates, to the age of 7–9 months, when CT scanning was performed. The interventricular septum was well visualized using i.v. bolus injections (0.5 ml/kg) of meglumine/sodium diatrizoate. Septal wall thickness was measured using a computer region of interest program that allowed myocardial edge detection. After CT scanning, the dogs were sacrificed. The hearts were excised and sectioned at the same levels as the CT scans were obtained. A linear regression for septal wall thickness as measured by CT and by autopsy was calculated CT\text{mm} = 1.15 (autopsy\text{mm}) - 3.64 (r = 0.92 for n = 14). The correlation between CT and autopsy values was excellent, although CT consistently underestimated the interventricular septal thickness by 10–20%. The explanation for this underestimation is not clear. Nongated CT scans appear to represent a composite image of the heart obtained during several heart beats. Systolic and diastolic variation in wall thickness as well as the method used for boundary detection are potential sources of error in this CT study. However, CT appears to offer a useful noninvasive method for estimating septal wall thickness and has the potential for providing measurements of total myocardial mass. CT scanning should be readily applicable in the clinical situation.

MAJOR DYNAMIC CHANGES in myocardial wall thickness have been documented using a variety of techniques.\textsuperscript{1–13} Wall thinning may occur after myocardial infarction or ischemia and frequently accompanies regional myocardial motion abnormalities. Conversely, an increase in myocardial mass is associated with a host of acquired and congenital disorders, notably obstructive lesions, that produce a ventricular pressure load.

The degree and extent of hypertrophy are difficult to assess but may be of considerable diagnostic and prognostic significance. Many invasive and noninvasive techniques are indirect and cannot provide precise measurements of regional wall thickness.

Computed transmission tomography (CT) scanning, a relatively noninvasive technique, offers transverse tomographic imaging in conjunction with high-density resolution and theoretically can provide reliable measurements of regional wall thickness and total myocardial mass. Cardiac structures can be successfully imaged in vivo by nongated and gated contrast-enhanced CT scanning.\textsuperscript{14–16} Quantitative studies of cardiac dimensions have been performed with CT scanning in excised canine hearts and showed good correlation with autopsy measurements.\textsuperscript{17} No previous study, however, has explored the potential of this method in the living state. We report a study undertaken to evaluate CT for measuring the thickness of the interventricular septum in vivo.

Materials and Methods

Fourteen pedigreed beagle puppies of both sexes made up the study population. Seven underwent surgery at the age of 6–8 weeks. The ascending aorta was exposed and a coarctation was created by banding with umbilical tape approximately 1–2 cm above the aortic valve. The aortic circumference was reduced 25–40% to produce an intraoperative thrill and a postoperative bruit. The operated dogs were then followed, along with their seven normal litter mates.

CT Scanning

The study was performed using a General Electric CT/T Research Scanner (modified GE whole-body scanner model CT/T 7800). This scanner has the capability of rapid sequence scanning, performing up to 12 360° scans in 40 seconds. Each has an exposure time of 2.4 seconds. The resolution and radiation dose efficiency are similar to the GE CT/T 7800.

The scanner can also produce projection "scout-view" computed radiographs. This radiograph resembles a conventional plainfilm but the image can be manipulated by adjusting the gray-scale window settings. The computed radiograph image is obtained by pulsing the x-ray tube with the detector array in a stationary position while the dog is moved through the x-ray field. The lateral scoutview was used to locate the cardiac apex, and all subsequent scans were indexed to this reference level (fig. 1).

The 14 dogs (age 7–9 months, weight 9–12 kg) were
anesthetized with a combination of intramuscularly administered xylazine and ketamine hydrochloride and ventilated through a cuffed endotracheal tube connected to a Harvard pump respirator. An 18-gauge intravenous catheter was introduced percutaneously in the right external jugular vein through which contrast medium was administered. The dogs were placed in a plexiglass cradle and transported to the CT scanner. The scoutview and the CT scans were performed during fixed maximal insufflation. The ECG was monitored and the heart rate was typically maintained at 50–80 beats/min by administering xylazine when required. Initially, 10-mm-thick CT scans from the cardiac apex to the base were performed before contrast medium administration. Suitable scan levels were then selected from this series of images for sequential scanning. Meglumine/sodium diatrizoate (Renografin 76, 0.5 ml/kg) was administered as a bolus injection 7 seconds before the first of 12 sequential 10-mm-thick scans that were obtained during the passage of the contrast medium bolus through the right and left side of the heart (fig. 2).

The projection data of a CT scan are processed by computer and the image composed of 320 × 320 picture elements (pixels) is displayed on a black-and-white television monitor. Each pixel represents a cross-sectional area of 1.3 mm × 1.3 mm. The brightness of a pixel is directly proportional to the x-ray attenuation coefficient of the tissue present at the corresponding point in the object's cross section. The quantity displayed is not the actual attenuation coefficient, but a quantity (the CT number) derived from the equation:

\[ \text{CT no.} = \frac{1000(A-A_w)}{A_w} \]

where A is the computed attenuation coefficient and \( A_w \) is the attenuation coefficient of water. Consequently, water is calibrated to 0 and air to -1000. The TV monitor allows a windowed display system where values of absorption above and below the window range are displayed as black or white, respectively, and those within the window width are displayed over a gray scale.

**CT Analysis**

This CT study was performed without ECG gating. Each scan of 2.4 seconds included several cardiac cycles. Because diastole is longer than systole, the CT images (and accordingly septal thickness) will theoretically reflect more of the diastolic (thinner) than the systolic (thicker) phase.

The scans that best outlined the midportion of the interventricular septum were chosen for analysis (figs. 3A and B). These scans were obtained when the contrast medium was present in both ventricular cavities. The scan level was usually located 30–40 mm from the

**FIGURE 1.** Computerized lateral radiograph of the supine dog. A vertical line marks the cardiac apex, which acts as a reference index level for subsequent computed transmission tomographic scans.

**FIGURE 2.** Six sequential 10-mm-thick computed transmission tomographic scans through the midportion of the interventricular septum. The scans were obtained after an i.v. bolus injection of contrast medium. The septum (arrows) is well demarcated in panels S5 and S6. The right ventricle (RV) and left ventricle (LV) can also be seen.
cardiac apex. The selected scans were displayed on the TV monitor and a rectangular region of interest was selected by cursor to include the septum and portions of both ventricular cavities (fig. 3B). The absolute CT numbers of all the pixels enclosed in this region of interest were printed out on a terminal printer as a pixel map (fig. 4A). The boundary between the myocardium and the denser chambers was defined as halfway between the mean CT number of the respective ventricular cavities and the mean CT number of the midportion of the myocardium. The mean CT number measurements were obtained by placing the cursor at different locations to exclusively include either the cavity or myocardium. The computer calculates the mean CT number of the pixels within the cursor at each desired location. The CT number defining the interface was then drawn on the pixel map. Since the pixel printout has a different $x$ and $y$ scale the true interface was obtained by plotting these on graph paper. A best-fit line was then drawn on the scale drawing and the average of several measurements was taken as the mean width of the septum (fig. 4B). In some studies the septal width was also measured directly on the TV monitor using a software program that calculates the distance between two cursor locations defined by the operator. However, variation of window settings and gray-scale levels made direct measurements of this type inconsistent. The pixel map with absolute CT numbers was therefore used throughout this study.

**Postmortem Studies**

The dogs were sacrificed by an overdose of intravenous sodium pentobarbital after CT scanning. The hearts were excised after cardiac standstill and appeared dilated and flaccid, the right ventricle more so than the left. The right ventricular wall, atria, aortic and mitral valves and the epicardial fat were removed. The left ventricular compartment, which consisted of the septum and the left ventricular free wall, was cut in 1-cm slices from apex to base. These slices were made perpendicular to the approximated long axis of the dog so that they corresponded to the CT scans. Several measurements of the septum were then made with calipers at different points along the septum and an average of these measurements was taken to represent the average autopsy septal width.

**Results**

High-quality, nongated CT scans were obtained in this study despite cardiac motion. The septum could easily be seen and was well demarcated when the contrast medium was present in each ventricle (fig. 2).

The mean ratio between the left ventricle (in grams) and the body weight (in kilograms) in the banded dogs was $10.3 \pm 2.05$ (SD) and $4.7 \pm 0.7$ (SD) for the normal control group. A ratio of 5.5 or greater confirms left ventricular hypertrophy. The dog model with increased afterload used in this study produces concentric hypertrophy. A typical CT scan through the midportion of the septum in a normal control dog is illustrated in figure 3A and a dog with left ventricular hypertrophy is depicted in figure 3B. The dramatic increase in wall thickness in the banded dog involves the ventricular wall as well as the septum and the cavity appears typically smaller than in the litter-matched control. A linear regression line for septal wall thickness was obtained by plotting the CT estimates against the direct autopsy measurements (fig. 5), and a good correlation was found:

$$CT = 1.15 \text{ (autopsy)} - 3.64$$

The correlation coefficient was 0.92 for the 14 experiments.

Nongated CT therefore underestimated the autopsy septal thickness by 10–20%. However, this was a consistent underestimation.

**Discussion**

Left ventricular hypertrophy is usually diagnosed by electrocardiography using criteria established 30 years ago. This technique is relatively sensitive, but lacks specificity because it is adversely affected by left bundle branch block, pericardial effusion and obstructive lung disease. It is therefore semiquantitative and indirect, although routinely useful in clinical practice. Angiocardiology has also been used as an indirect method for obtaining left ventricular mass, but results are based upon relatively few measurements. It assumes, furthermore, that the myocardial wall thickness is uniform; this is seldom the case. The method cannot estimate right ventricular wall dimensions and is invasive. Echocardiography is a direct, noninvasive approach. One-dimensional studies are not felt to be reliable. Two-dimensional sector scanning is being explored for this purpose. Fundamental difficulties, including lung disease, pericardial effusion, interspace window restriction, and transducer...
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**TOTAL NUMBER OF PIXELS SAMMELED:** 288.
**MEAN:** 54.74
**STANDARD DEVIATION:** 27.95

REPLOTTED PIXEL MAP

![Pixel Map Diagram](image)

**Figure 4.** A) Computer printout of absolute computed transmission tomographic (CT) numbers present within the same region of interest as described in figure 3B. Each pixel is 1.3 × 1.3 mm. Lines demarcate all pixels with absolute CT numbers of 60 or less, thus defining the interventricular septum. This boundary CT number was defined as the CT number that was halfway between the mean CT number of the cavities and the mean CT number of the midportion of the septal wall. B) Scale drawing of the septum, defined within the region of interest, from which the mean width is calculated.

tilting requirements make precise measurements at given levels difficult. Ventricular shape, orientation and intracavity trabeculations disproportionately influence calculations of this type. Echocardiography nevertheless has established itself as the best noninvasive clinical method for obtaining such dimensional information. The examinations are simple and relatively inexpensive. However, an accurate noninvasive method that is less dependent upon individual experience regarding transducer manipulation and image interpretation is needed. CT scanning with intravenously administered contrast medium offers such
seem the tomographic throughout autopsy along a number of projections together and estimates lie on the ordinate.

Compared with the autopsy measurements, CT consistently underestimates wall thickness by 10–20%. This underestimation is surprising and is not easily explained. Cardiac motion and the partial volume effect, that is, averaging of density in structures only partially included in a slice, would be expected to overestimate dimension measurements with CT. The underestimation might be due to postmortem changes or may lie in our method for determining the myocardial boundary. At postmortem examination, the hearts appeared to be in diastole. Postmortem heart measurements were then compared with the nongated CT scan measurements exposed during two to four heartbeats. Hence, each scan represents an average of several heartbeats, and probably more of diastole. Therefore, we believe that the heart is approximately in the same phase of the cardiac cycle during CT imaging as at post-mortem. Consequently, postmortem changes do not seem to be the likely major source of error.

In our experience and that of others, in vitro CT study measurements of the septum correlated well with those obtained at autopsy. Figure 6 illustrates a possible explanation — the method we chose to define the myocardial boundary. The CT number chosen for identifying the boundary between the myocardium and the ventricular cavities may be too low, in which case the CT measurements obtained for the septum would indeed be underestimated. Further investigations to define the source of this discrepancy are desirable, such as recording septal wall thickness by implanted piezoelectric crystals in conjunction with gated and nongated CT scanning. CT phantom studies may also be helpful in determining the role of cardiac motion on CT estimates of septal wall dimensions during the normal cardiac cycle.

This study should encourage further quantitative experiments to determine the value of CT for obtaining other cardiac dimensions. Animal experiments such as the one described here are essential for determining the feasibility and accuracy of quantitative CT methods. Future efforts should be directed toward comparing CT with other invasive and noninvasive techniques. The hope for extending CT quantitative methods to patients depends upon prior validation studies in animals. The application of CT in the clinical setting will become more frequent as advances in CT technology appear.
References

1. Sokolow M, Lyon TP: The ventricular complex in left ventricular hypertrophy as obtained by unipolar precordial and limb leads. Am Heart J 37: 161, 1949
Assessment of ventricular wall thickness in vivo by computed transmission tomography.
C G Skiöldebrand, C O Ovenfors, C Mavroudis and M J Lipton

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