Determination of Right Ventricular Mass in Humans and Dogs With Ultrafast Cardiac
Computed Tomography

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There is currently no clinical approach to precisely measure right ventricular (RV) mass. We
postulated that the radiological mode of ultrafast computed tomography (CT) of 3-mm-thick
slices with 0.7-mm resolution would allow sufficient resolution to accurately estimate RV mass.
Using this radiological mode, we serially imaged the entire right ventricle from apex to base,
gated to end diastole, and applied Simpson’s rule to calculate mass of the RV free wall. Thirteen
mongrel dogs (weight, 6–30 kg) were studied. The free wall mass of the right ventricle was in
the range of 12.0–47.5 g and averaged 35.4±3.7 g (mean±SEE). The correlation between RV
mass estimated by ultrafast CT and actual RV mass was r equaling 0.85, SEE equaling 5.5 g,
slope equaling 0.99, and y intercept equaling −1.8. Intraobserver and interobserver variability
(r=0.99 and r=0.99, respectively) was excellent with a standard deviation (SD) equal to 1.5 and
1.8, respectively. The effect of variable RV preload (right atrial pressure, −5 to +20 mm Hg) on
accuracy of RV mass measurements produced minimal error (SD=3.6 g) in RV mass
measurements. Seven normal young healthy men were also studied. The free wall mass of the
right ventricle was in the range of 48.3–67.4 g and averaged 54.6±2.8 g (mean±SEE). The left
ventricular to right ventricular (LV:RV) ratio averaged 3.2±0.2:1. These results are in
agreement with human autopsy data in healthy males reporting mean RV mass equal to 46 g
and an LV:RV ratio equal to 3.4:1. Because imaging every 3-mm slice from apex to base
requires two contrast injections, we determined the accuracy of RV mass measurements if only
every fourth 3-mm slice with interpolation was used. RV mass measurements using every slice
or every fourth slice with interpolation were excellent (dogs, r=0.99; humans, r=0.97). It is
concluded that high resolution CT imaging (3-mm tomograms) allows accurate measurements
of RV mass. It is possible to add this stop-action mode of ultrafast CT, to previous CT studies,
using every fourth tomographic slice for mass determinations and only one additional contrast
injection of 40–60 ml. This should permit the study of progression and regression of RV mass
in patients with various diseases. (Circulation 1990;82:202–212)

Precise estimates of right ventricular (RV) volume and RV mass are much more difficult to
obtain than similar measurements of the left ventricle. The explanation for this difference is

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1990.
volume (i.e., biplane angiography,14,15 radionuclide angiography,16–18 and ultrafast CT11). The literature is devoid of any convincing validation studies of noninvasive estimates of RV mass. Such a technique, if perfected, could permit the study of progression and regression of RV hypertrophy in various disease states and its impact on patient outcome. Existing methods, that is, electrocardiography,19,20 echocardiography,21–25 radionuclide angiography,16–18 and thallium-201 imaging,26–28 primarily provide a qualitative or semiquantitative estimate of RV volume, mass, or a combination of the two.

Previous ultrafast CT studies of RV volume have been precise and reproducible,11 whereas RV mass studies have not been attempted. Now, with the improved resolution with ultrafast CT (3-mm thick and 0.7-mm resolution), the RV wall thickness is easily visualized and RV mass can be estimated. We attempted to document the precision of measurements of RV mass with high-resolution ultrafast CT.

Methods

Ultrafast Computed Tomographic Scanner

The mechanics of the ultrafast CT scanner (model C-100, Imatron, Inc., South San Francisco) have been described previously.11–13 Magnetic deflection of an electrocardiographically (ECG) triggered electron beam results in rapid sweeping across one of four semicircular tungsten targets that surround the subject, producing 3-mm-thick tomograms in 100 msec. Triggered and precise table movement between scans allows for contiguous 3-mm tomograms. As many as 20 multilevel scans in rapid sequence can be taken during a single contrast injection. During infusion of intravenous contrast, ECG-triggered tomograms can be obtained at a designated time during each cardiac cycle. This allows for stop-action scans to be obtained during continuous infusion of circulating contrast. The system performs image reconstruction comprised of 512x512 pixels. Therefore, with a 26-cm diameter reconstruction circle, each pixel represents an area of approximately 0.25–0.5 mm². The spatial resolution is 0.7 mm. This is more than adequate resolution to analyze the RV wall with a previously reported thickness in human subjects of 3.0–4.0 mm.1

With a 0.26-mm² pixel area and 3-mm scan thickness, the smallest possible three-dimensional volume obtained is approximately 0.8 mm³. This represents 8x10⁻⁴ g myocardium, and implies that this technique is very accurate.

Canine Preparation

Thirteen mongrel dogs (weight, 6–30 kg) were anesthetized with an intravenous combination of droperidol and fentanyl (Innovar-Vet) 0.1 ml/kg and sodium pentobarbital 10 mg/kg, and mechanically ventilated with room air through a cuffed endotracheal tube and maintained on 3–4 cm (water) of positive end-expiratory pressure. By a percutaneous Seldinger technique, 5F femoral venous and arterial catheters were placed, flushed with heparinized saline, and connected, respectively, to an intravenous solution of 0.9 normal saline and to intravenous tubing and a pressure transducer for continuous monitoring of arterial pressure. In five dogs, an 8F sheath was also placed percutaneously in the right internal jugular vein, and through it, a 7F thermocouplUon Swan-Ganz catheter was advanced into the superior vena cava/right atrium (RA). In three of these dogs, through a separate femoral vein approach, a Swan-Ganz catheter was advanced into the main pulmonary artery and the balloon was inflated to 10 ml to augment RV end-diastolic pressure. These dogs also had an 18F Foley catheter placed in the inferior vena cava through a femoral vein cut-down to rapidly decrease venous return by Foley balloon inflation. Anesthesia was maintained by supplemental doses of sodium pentobarbital as needed. Electrodes were attached to each dog for continuous monitoring of the heart rate and to provide a trigger signal to the scanner.

Patient Studies

Studies were performed in seven men (age, 21–29 years). All had a normal physical examination, and normal glucose, creatinine, and uric acid levels. Trained athletes were excluded from the study. All subjects provided informed consent and were studied in compliance with a protocol previously approved by the Human Use Committee at the University of Iowa. Scans were performed after a 4-hour fast, and no premedications were administered. After placement of electrocardiographic monitoring leads, an 18-gauge, 2.5-in. angiographic catheter was placed in an antecubital vein and circulation time was measured by injection of 10 ml dilute magnesium sulfate (0.5%).12

Data Acquisition

Canine studies. After completion of the surgical preparation, the dog was transported to the cine CT scanning facility. The table was positioned at a +15° slew to the right (posterior) with respect to the body’s long axis, in the horizontal position to best view the short axis of the heart. With the dog in the right lateral decubitus position, non-contrast-enhanced localization tomograms were performed to determine appropriate levels of scanning to image the entire heart apex to base. Thereafter, 20 stop-action end-diastolic ECG-triggered scans were performed at 3-mm increments (contiguous). Nonionic contrast (Iohexol [Winthrop Pharmaceuticals, New York], 350 mg iodine/ml) was injected intravenously by a power injector at 2 ml/sec, beginning at 15 seconds before imaging and throughout scanning to ensure adequate opacification of the left and right ventricles throughout scan acquisition. A total of 2–3 ml/kg of Iohexol was required to image the entire heart. The ventilator was turned off for the approximately 30-second scanning sequence to prevent respiratory motion artifact. Systemic arterial pressure and, in five dogs, right atrial pressure were continuously moni-
tored. In the latter five dogs, the entire scanning sequence was repeated at three levels of right atrial pressure.

After the completion of the study, the dogs were killed with an intravenous injection of potassium chloride. Their hearts were removed and fixed in formalin. The RV free wall with trabeculae was then dissected from the left ventricle and atria. Free hanging RV trabeculae were trimmed to the septal wall. Valvular tissue and fat were carefully excised, and the myocardium was weighed to the nearest 0.01 g. Additionally, three of the canine hearts were weighed both before and after formalin fixation. The values differed by only 2%.

Patient studies. The scanning protocol was similar in the human studies. The subject was positioned at −25° and −15° elevation (head elevated), relative to the long axis of the table to best visualize the short axis of the heart. A noncontrast-enhanced localization scan was performed to determine the level of the ventricular apex. During scanning, the subjects suspended respiration at end inspiration without performing a Valsalva maneuver. Nonionic contrast (Iohexol, 350 mg iodine/ml) was injected intravenously with a power injector at 1.5–2.0 ml/sec. Injection began 10–15 seconds before and continued throughout scan acquisition. ECG-triggered scanning began after the patient’s circulation time elapsed. Tomograms were performed at 3-mm increments (contiguous) and, in three subjects, at both 3-mm and 9-mm table increments. Only one contrast injection was required to image the entire right ventricle by using 9-mm table increments (20 levels) versus two or three injections for the 3-mm contiguous slice scanning sequence (40 levels). A total of 2–3 ml/kg contrast was required to obtain all scans per subject.

Border definition. Specific criteria have been previously described by our laboratory for edge detection of the regions encompassing the interfaces between the lung and epicardium, LV cavity and adjacent endocardium, RV cavity and right endocardial edge of the septum, and anterior chest wall and myocardium for LV mass measurements. Feiring’s half-contour method involves computer-assisted edge detection to define borders where partial voluming impairs manual trackball outlining. It is based on computer-defined borders where CT density is halfway between the densities of bordering structures. These criteria were used in this study to determine the epicardial-lung interface and the ventricular cavity–endocardial interface.

When defining the right ventricle by ultrafast CT data, there were three borders that required judgment decisions to delineate, that is, the RV epicardial surface where the right ventricle is adjacent to the liver, the tricuspid valve plane, and the pulmonic valve plane. At the levels where the RV myocardium and liver were adjacent and had the same CT density, a line was extrapolated by hand using a trackball to produce a constant RV wall thickness in that region.

The criteria for identification of the tricuspid valve plane included the presence of the sharply defined tricuspid valve, the absence of a thick rim of myocardium surrounding the RA, the occasional observation of the right coronary artery in the atroventricular groove, a higher intensity of contrast material in the RA due to its closer proximity to the injecting catheter, or any combination of these criteria. The separation of the RV outflow tract from the pulmonary artery was defined by the pulmonic valve plane that could usually be visualized. When it could not be clearly seen, we arbitrarily set a vertical valve plane at the most caudal slice where RV myocardium was still visible.

Contiguous tomograms. The entire right ventricle from apex to base was traced as previously validated in our laboratory, resulting in planimetry of one area encompassing the end-diastolic RV cavity plus RV free wall, and a second area, the RV cavity. The tomographic measurement of RV free wall area was determined at each level as the difference of these two planimetered areas. These calculations at each level were added by use of Simpson’s formula, that is, at each level, the RV myocardial mass was calculated as a product of the planimetered RV myocardial area, the scan slice thickness (3 mm), and the specific gravity of the myocardium (1.05/cm³). The RV myocardial mass was calculated as a sum of the masses of the individual scanned sections.

Interpolated data. In all studies, we also determined the accuracy of RV mass measurements if only every fourth 3-mm slice from the same scan (with 9-mm interpolation) was used in the calculations. In three human studies, we also analyzed separate scans with actual 9-mm increments between images. The masses were calculated in a similar fashion using 9-mm interpolation.

Reproducibility. Intraobserver variability was determined by analysis 4–5 weeks later of the same complete scan with the observer blinded to the actual study. Interobserver variability was determined by analysis by different investigators of the same complete scans. Each observer was required to independently define the lowest and highest levels where the right ventricle was seen and the location of the valve planes. Random dog scans were chosen by a third person to represent various weights across the entire range of available RV masses.

Human studies. Because no postmortem ventricular weights were available in our human studies, the LV and RV masses were compared as a ratio. LV mass determination has been previously validated by using 8-mm-thick tomograms in the movie mode. In our human studies, LV mass was determined in the same manner as RV mass determination previously described. LV cavity plus wall, and LV cavity planimetry were done at each tomographic level. LV myocardial area was determined as the difference between these two planimetered areas. LV mass per slice was calculated as a product of planimetered LV myocardial area, scan slice thickness (3 mm), and
myocardial specific gravity. The tomographic masses at each level were summed.

Statistical Analysis

Canine studies. Statistical analysis was performed using linear regression by least-squares fit on 13 dog values comparing in vivo RV mass derived by ultrafast CT scanning with the postmortem RV mass. The linear correlation coefficient, slope, y-intercept, and the standard error of the estimate were calculated. An F test was used to determine if the slope of our regression relation significantly differed from 1.0 and if the y-intercept significantly differed from 0. Interobserver and intraobserver variability were calculated using linear regression for five representative dogs in which RV mass spanned the entire range of available masses. Interpolated data on RV mass measurements from the same dog using every fourth slice were compared with measurements obtained from each contiguous slice by linear regression analysis as well. The RV mass data derived under variable loading conditions were analyzed by comparing with a variance-ratio F test, the standard deviation for repeat measures, with the standard deviation for intraobserver and interobserver variability. The RV mass data obtained under variable loading conditions were also compared by fitting least-squares regression lines of the data for each dog using pressure and volume separately as the predictor variables and comparing the slopes to zero. Statistical significance was defined as a p value of less than 0.05.

Human studies. Because no postmortem ventricular weights were available in our human studies, the ultrafast CT–obtained LV and RV masses were compared as a ratio (LV:RV) to pooled previously published human autopsy data in healthy males.29,30 The 95% confidence interval was used to define measurement equality. Linear regression analysis was used to compare RV mass measurements obtained using every fourth slice with measurements obtained using every slice from the same scan. Additionally, a repeat measures analysis of variance (ANOVA) was used to compare RV mass in three individuals who had contiguous measurements, interpolated measurements, and measurements from a separate scan with 9-mm table increments. Statistical significance was defined as a p value of less than 0.05.

Results

Baseline Data

Data are presented for 13 dogs (weight, 6–30 kg). Heart rate averaged 95±5 beats/min. Right atrial pressure in five dogs was altered by rapid infusion of saline, pulmonary artery balloon inflation, Foley balloon inflation in the inferior vena cava, or any combination of the three. The right atrial pressure varied from -5 to 20 mm Hg.

Data in seven men revealed a mean heart rate of 73±4 beats/min.

The data acquisition time for a 20-level 3-mm increment run was 20–40 seconds, depending on the heart rate. Eighteen to 30 contiguous tomographic slices were required to scan the entire right ventricle in dogs; approximately 32–40 contiguous slices were needed to image the entire human right ventricle. In some subjects, therefore, two 20-level scans were required.

Postmortem Right Ventricular Mass Versus Cine Computed Tomographic Right Ventricular Mass

Figure 1 shows a typical 3-mm-thick tomographic scan taken of a dog at the mitral valve level. Note the clear visualization of RV wall thickness. Figure 2 shows a different dog scan at the midventricular level with borders outlined as described in “Methods.”

Figure 3 shows the results of ultrafast CT determination of RV mass compared with autopsy-derived RV mass for all 13 dogs. The free wall mass was in the range of 12.0–47.5 g and averaged 35.4±3.7 g. The slope and y-intercept were not statistically different from 1 and 0, respectively (p>0.10).

Intraobserver and Interobserver Variability

The intraobserver and interobserver variability of eight scan sequences from five dog studies was excellent [intraobserver variability, r=0.99, y=(0.99 x)−0.21, SD=1.5 g (Figure 4, left panel); interobserver variability, r=0.99, y=(0.91 x)+2.8, SD=1.8 g (Figure 4, right panel)].

Right Ventricular Mass at Various Loading Conditions

The effect of variable RV preload on accuracy of RV mass measurements was studied in five dogs at two to four levels of right atrial pressure. Table 1 shows the ranges of right atrial pressure and RV volume obtained for each dog and the respective CT-derived and autopsy masses. The standard deviation for repeated estimates of RV mass at different loading conditions (SD=3.6 g) was not statistically different than the standard deviation obtained for repeated measurements for intraobserver and interobserver variability (SD=1.5 g and SD=1.8 g, respectively). Additionally, there was no consistent change in CT-derived RV mass at increasing right atrial pressures (p=0.98) or increasing RV volumes (p=0.31).

<table>
<thead>
<tr>
<th>RA pressure (mm Hg)</th>
<th>RV volume (cc)</th>
<th>CT-derived RV mass (g)</th>
<th>Autopsy RV mass (g)</th>
</tr>
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<tr>
<td>(−) 2–12</td>
<td>16–19</td>
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<td>(−) 5–(−)3</td>
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<td>59–63</td>
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RA, right atrial; RV, right ventricular; CT, computed tomography. Ranges were obtained by varying the preload as described in “Methods.” Actual (Autopsy) RV mass is also shown for the five dogs studied.
FIGURE 1. Photomicrograph showing typical appearance of a 3-mm-thick tomogram of a dog heart taken at the level of the mitral valve.

FIGURE 2. Photomicrograph showing 3-mm-thick tomogram of a dog heart taken at the midventricular level with planimetered borders as described in “Methods.” A encloses right ventricular free wall and cavity, B outlines right ventricular cavity.
Human Studies

Figure 5 shows a typical scan obtained from a human at the midventricular level. Figure 6 illustrates a scan from the mitral and tricuspid valve level with borders outlined as described in "Methods."

In the seven men, the free wall mass of the right ventricle was in the range of 48.3–67.4 g and averaged 54.6±2.8 g. The LV:RV ratio averaged 3.2±0.2:1. These results were compared with human autopsy data in healthy males,29,30 which reported mean RV mass equal to 46 g and LV:RV ratios of 3.4:1 (Figure 7). The 95% confidence interval for the ratio from CT-derived RV mass (2.8:1 to 3.6:1) includes the autopsy ratio of 3.4:1.

Interpolated Data

RV mass measurements using every contiguous slice (with 3-mm interpolation for slice thickness) or every fourth slice (with 9-mm interpolation) from the same scan sequence were nearly identical in dogs \( r=0.99, y=(1.02 x)-0.44 \) and in humans \( r=0.97, y=(1.04 x)-1.7 \).

In three humans, data from a different scan sequence performed approximately 10 minutes later at the same mean blood pressure and heart rate, using actual 9-mm table increments, revealed nearly similar results compared with 3-mm contiguous slice scans and every fourth slice interpolated measures (repeat measures ANOVA, \( p>0.50 \). The aggregate data of 10 humans (seven imaged with contiguous 3-mm table increments but using every fourth slice with 9-mm interpolation for computation of RV mass, and three humans studied with actual 9-mm table increments) showed reliable results when compared with paired contiguous scan data \( r=0.86, y=(0.75 x)+12.9 \). The difference between the two methods was 3.3±1.3 g, which equals 6±2% (range, 1–15%) difference.

Discussion

This study describes the first successful approach to noninvasively measure RV mass precisely in vivo. With high-resolution cine CT imaging, accurate reproducible determination of RV mass in dogs and humans can be obtained.

Accuracy of Right Ventricular Mass Measurements

Previously validated alternative methods of assessing RV geometry are qualitative or only semiquantitative, at best.

Validations of multiple electrocardiographic criteria for RV hypertrophy have revealed that estimates of RV mass by electrocardiography might be specific but are very insensitive. Indeed, estimations by electrocardiography19,20 are poor predictors of absolute RV mass.

Echocardiographic evaluation of RV volume can be fair in some instances, but mass estimates are poor. M-mode evaluation is simply not reliable, and
FIGURE 5. Photomicrograph of typical appearance of a 3-mm-thick tomogram from a human heart at the midventricular level.

FIGURE 6. Photomicrograph of a 3-mm-thick tomogram of a human heart taken at the level of the mitral valve with planimetered borders as described in “Methods.” A encloses right ventricular free wall and cavity, B encloses right ventricular cavity.
two-dimensional imaging is hampered by limited acoustic windows, application of few echocardiographic views to estimate global geometry, and errors associated with poor resolution of the trabeculated and irregularly shaped right ventricle.21-25

Radionuclide angiography has been widely used for estimation of RV volume and function. The technique is suitable for evaluating size and performance because it is relatively independent of geometry and can be repeated easily, but it lacks the capability of assessing wall thickness and RV mass.16-18

Thallium-201 imaging has demonstrated increased RV wall thickness in patients with pulmonary hypertension, even when RV hypertrophy is not detected by electrocardiography.26 Because of poor resolution, this semiquantitative technique has only fair specificity and poor sensitivity.26-28

Biplane angiography allows for estimates of RV volumes by analysis of the cardiac silhouette. Limited views produce errors in estimates of volume, and no wall thickness measurements are possible for mass determination.14,15

Finally, magnetic resonance imaging studies might be useful in analysis of RV geometry9 and mass because of their tomographic nature and adequate spatial resolution. Thus far no validation studies exist for assessing RV mass with magnetic resonance imaging.

The accuracy of our in vivo measurements of RV mass in dogs was validated by comparison with postmortem formalin-fixed RV weight. The accuracy of measurements made using fixed specimens has been established31 and introduces minimal (3%) error. When three of our canine right ventricles were weighed both before and after formalin fixation, they differed by only 2%.

The human data reported on RV mass and LV:RV ratios are compared with existing pathological data in healthy human hearts. Because no noninvasive studies exist comparing estimated to actual RV weight, these data represent the first attempt at such a correlation.

Theoretically, thinner tomographic slices should improve the accuracy of ventricular mass measurements.31 Imaging using the thinner 3-mm tomographic slices from apex to base, however, requires two or more contrast injections, longer breath-holding, and might introduce variability in hemodynamic conditions between the different scans. We, therefore, determined the accuracy of RV mass measurements if only every fourth 3-mm-thick slice was used, interpolating for a theoretical slice thickness of 9 mm instead of 3 mm in all 13 dogs and 7 men. The results reveal that RV mass measurements are equally as precise when obtained by either method, across a wide range of RV weights. To assess the feasibility of 9-mm interpolation, three human subjects had tomograms performed at both 3-mm and 9-mm table increments. This also produced reliable results.

Limitations and Risks

The current mode of obtaining stop-action scans during a steady-state contrast infusion is highly dependent on several factors. The presence of a regular cardiac rhythm is crucial for optimum acquisition because irregular rhythms and premature beats can cause inaccuracies by producing scans at different portions of the cardiac cycle. Consequently, measurements in patients with grossly irregular rhythms will be less accurate than determinations made in those patients with regular rhythm.

Additional limitations arise when the ventricular cavities are not adequately opacified. This can occasionally produce problematic tomograms. We have already described the method of extrapolating by hand using a trackball, a line, separating the RV myocardium from the adjacent liver when they have the same CT density. This would usually involve only a short distance and should not introduce much error.

Inadequate opacification can also produce an image in which the pulmonic or tricuspid valves are not easily seen. At the tricuspid valve, this problem could be handled by tracing the border where high and low
intensity of contrast suddenly equilibrate. This presumably represents mixing of contrast-containing and non-contrast-containing blood in the RA, bordering on the well-mixed RV cavity (Figure 6).

At the pulmonic valve, when inadequate opacification produces poor visualization of the valve, the border tracing is aided by the RV myocardium, which suddenly narrows into a thin-walled pulmonary artery at this point. The tracing involves arbitrarily setting the pulmonic valve at this position (Figure 8), which is typically vertical.

A potential problem, which we did not encounter, is inadvertently mistaking RV trabeculae for non-contrast-containing regions of the RV cavity. With proper mixing of contrast by injection into a peripheral vein this problem should be minimal.

An additional potential source of error has to do with the imaging of a three-dimensional crescentic semisphere. At most tomographic levels, the RV myocardium is viewed perpendicular to the short axis of the heart. At more apical levels, the angular orientation of the RV free wall is such that it can appear thicker than at more basilar levels and can seem to approach the thickness of the interventricular septum (see Figure 2). Despite this apparent thickening of apical tomographic levels, our Simpson's rule estimation of RV mass was in excellent agreement with actual postmortem measurements. Because few apical tomographic levels are included in this reconstruction, the source of error introduced was probably minimal. It remains to be shown whether the study of volume-overloaded or pressure-overloaded right ventricles with greater radii might have greater error due to this oblique imaging.

When human studies required more than 20 levels to image the entire ventricle, a second scan was performed several seconds later beginning at a contiguous level without scan overlap. Because of this, two separate breath-holds at end inspiration needed to be performed. With this maneuver, the position of the heart in the thoracic cavity might have changed somewhat between the two scans. Patients were instructed not to move during the time between the two 20-level scans to prevent error from changes in body position; however, differences in tidal volume between scans and between subjects might have affected the results. The routine use of 9-mm increments between scan levels would obviate the need for more than one injection and decrease this potential source of error.

Risks involved with this procedure include an exposure to radiation and the risk from infusion of contrast material. The radiation exposure from the CT scanner is 5.4 rad per cine study and 0.84 rad per high-resolution study. In contrast, a typical dose for a chest x-ray is 0.05–0.1 rad, whereas the dose for a cardiac catheterization is approximately 5 rad per minute of fluoroscopy time or 10–100 rad. Thus, the CT radiation is significantly less than from a standard fluoroscopic procedure, and the dose is well within the safety limits set for diagnostic procedures. To minimize the possibility of adverse reactions to contrast infusion, patients with renal insufficiency, dehydration, or previous allergic reaction to contrast media need to be excluded.
Despite the excellent results possible with the new mode of ultrafast CT, there are several aspects requiring caution. First, this procedure has not been studied in very small infants. Several canine subjects with small myocardial masses were included and performed without difficulty, but it is hard to extrapolate this data to a small infant. Second, some skill is required to evaluate the scans and make certain determinations regarding configurations and myocardial anatomy. Third, this noncine mode of CT imaging requires at least one additional injection of contrast because this is not a standard mode for a routine patient study. In fact, to avoid excessive contrast injection, the studies reported for determination of LV mass were also performed in the stop-action mode and not in the movie mode as previously validated.\textsuperscript{13} With the use of 3-mm-thick slices at 9-mm increments, however, the number of levels required to image the entire right ventricle was decreased by one third, as was the amount of contrast injection required. The average amount of contrast used for human studies in the cine mode is approximately 120 ml. The stop-action 3-mm-thick tomograms require an average of 50 ml to visualize the entire right ventricle at 9-mm table increments. This totals 170 ml or 2.4 ml/kg in an average-sized 70-kg subject. This, therefore, should allow each subject to have thorough ultrafast CT studies (stop-action 3-mm-thick tomograms and movie images) without excessive contrast exposure and should provide data on both LV mass and volume, as well as RV mass and volume. This now makes the addition of 3-mm-thick tomograms to routine scans a practical option.

Applications and Usefulness of In Vivo Measurements

A reliable means to assess RV mass should have multiple applications. In fact, with future testing, it might be that like LV mass, which has been shown to be the single most important prognosticator of cardiac mortality,\textsuperscript{34} RV mass might also be useful in predicting morbidity and mortality in patients with right-sided heart problems. Also, gross estimates of RV wall stress or compliance can now be possible from measurements of RV mass and RV volume.

Conclusion

We have measured RV mass in humans and dogs with a high degree of accuracy and reproducibility. This approach represents the most accurate method of estimating RV mass in vivo. The technique is rapid and minimally invasive. It should have many useful applications in clinical studies.

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