Quantitative determination of aortic regurgitant volumes in dogs by ultrafast computed tomography

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ABSTRACT Current imaging modalities can provide only a qualitative or semiquantitative measure of the severity of aortic regurgitation. Ultrafast computed tomography (CT) has the capability of rapid imaging (17 frames/sec) coupled with high spatial resolution (1.5 mm²). Eight millimeter thick images can be acquired to interrogate simultaneously the right and left ventricles. End-diastolic and end-systolic tomograms can be reconstructed serially from apex to base by Simpson's rule to provide end-diastolic and end-systolic volumes from which the right and left ventricular stroke volumes can be derived. To determine whether the difference between left and right ventricular stroke volume measured with ultrafast CT could be used to estimate the volume of experimentally induced aortic regurgitation, we studied six dogs in which proximal aortic electromagnetic flow probes had been implanted. Varying degrees of aortic regurgitation were induced by manipulation of a basket catheter through the aortic valve. During suspended respiration in the control state in the absence of aortic regurgitation, right and left ventricular stroke volumes measured with ultrafast CT were nearly identical (mean difference 1.0 ± 1.2 ml [mean ± SE]). In the presence of varying degrees of aortic regurgitation, regurgitant volume derived by ultrafast CT as the difference between right and left ventricular stroke volumes correlated closely to the regurgitant volume measured by the electromagnetic flow probe (r = .99, slope = .92, y intercept = 0.98 ml, SEE = 1.02 ml, n = 16). Regurgitant fraction also correlated closely to the regurgitant fraction measured by the electromagnetic flow probe (r = .94, slope = .98, y intercept = 0.66%, SEE = 4.73%, n = 16). The results were highly reproducible, with minimal interobserver variability. Thus ultrafast CT is capable of precise measurements of both aortic regurgitant volume and regurgitant fraction.


AORTIC REGURGITATION is a disease process manifested by an array of heterogeneous symptoms and signs that make clinical evaluation of the severity of the disease quite difficult.1 The interval from the diagnosis of chronic aortic regurgitation to valvular replacement is highly variable, but the timing of operative intervention for aortic valvular replacement is crucial to prevent irreversible left ventricular dysfunction.2,3 The dilemma faced by the practitioner is to refrain from premature valvular replacement with the attendant risk of morbidity from long-term anticoagulation or prosthetic valve dysfunction yet to avoid delaying surgery to the point of irreversible left ventricular dysfunction.

To evaluate patients with aortic regurgitation, accurate serial quantification of the degree of aortic regurgitation over time by a reliable imaging modality would be clinically valuable, along with measurement of left ventricular mass and left ventricular volumes. Current imaging techniques have proved unsatisfactory in the assessment of the severity of aortic regurgitation. Angiography (and/or digital subtraction angiography) can provide only a qualitative estimate of the severity of aortic regurgitation.4–9 Doppler echocardiography can provide a semiquantitative measure of the regurgitant fraction in the presence of aortic regurgitation but has inherent limitations in reproducibility, primarily because of methodologic drawbacks.10–18 Radionuclide angiography has significant limitations that make accurate right and left ventricular measurements of stroke volume to derive regurgitant volumes difficult and unsuitable for serial examinations.19,20

Ultrafast computed tomography (CT) is a relatively new imaging modality that has high spatial and tem-
poral resolution and can obtain serial tomograms that interrogate the right and left ventricles nearly simultaneously. Reconstruction of these tomographic images from apex to base can be used to derive highly accurate left and right ventricular stroke volumes. If the right and left ventricular stroke volumes during suspended respiration are equivalent in the control state, then the difference between the right and left ventricular stroke volumes could provide a highly accurate measure of the actual regurgitant volume during aortic regurgitation. The purpose of this investigation was to determine in an animal preparation, in which aortic regurgitation could be precisely measured by an electromagnetic flow probe, whether the regurgitant volume could be derived accurately by ultrafast CT.

Methods

Ultrafast CT: technical details. The (Imatron C-100) scanner has a unique x-ray source that consists of the single-bend scanning electron beam (130 kV, 600 mA) that is magnetically focused and deflected onto four semicircular (210 degree) tungsten target rings. X-rays are detected with a stationary double array of 864 scintillation photo-diode crystals. Two levels at 8 mm thickness per level can be obtained from each target ring. Each target ring is separated by a 4 mm distance. Images are acquired at 50 msec intervals, with an 8 msec interscan delay. An 80 image movie (2 to 8 levels) can be acquired per scan. An eight-level, 10 frame/level, movie (580 msec acquisition time per level) can completely interrogate the cardiac cycle at heart rates of 103 beats/min or greater. A six-level, 13 frame/level, movie (754 msec acquisition time per level) can completely interrogate the cardiac cycle at heart rates of 80 beats/min or greater. A four-level, 20 frame/level, movie (1160 msec acquisition time per level) can completely interrogate the cardiac cycle at heart rates of 52 beats/min or greater.

The data acquisition system performs image reconstruction in a matrix comprising 256 x 256 picture elements (pixels). With a 25 cm reconstruction circle used in the animal experiments, each pixel represents a 1.016 mm² area. There are 2047 displayable shades of gray scale, with each pixel representative of a shade of intensity proportional to the characteristic tissue x-ray attenuation coefficient (Hounsfield unit). A video display monitor is integrated with the computer to allow operator interaction for analysis of the CT images.

Animal preparation. Six mongrel dogs (weight 20 to 35 kg) were anesthetized with intravenous Innovar-Vet (fentanyl-droperidol 0.1 mg/kg) and pentobarbital (15 to 20 mg/kg) and mechanically ventilated with room air. A left thoracotomy via the fourth intercostal space was performed under sterile technique to expose the heart and great vessels. An electromagnetic flow probe (16 to 18 mm in diameter) was implanted snugly on the proximal ascending aorta several centimeters above the aortic valve. A piece of Teflon mesh material (USCI) was cut to the dimensions of the aorta and tightly positioned around the ascending aorta before the insertion of the electromagnetic flow probe at the site. Both ends of the Teflon mesh material were wrapped with a 0.1 mm thick and 2 cm wide strip of Gore-tex material that also circumscribed the aorta. The connector to the probe was tunneled to an interscapular position and secured subcutaneously. The dogs were returned to the kennel for 10 to 14 days to allow fibrosis of the probe to the aorta and thus ensure optimum contact and to prevent detachment of the probe from the aorta because of the hyperdynamic arterial pulse obtained with the aortic regurgitation.

On the day of the study the dogs were returned to the laboratory and again anesthetized with Innovar-Vet (0.1 to 0.2 mg/kg) and pentobarbital (25 to 30 mg/kg) for the duration of the experiment. Throughout the experiment the dogs were intubated and mechanically ventilated with room air and 3 to 4 cm of positive end-expiratory pressure. A No. 8F pigtail catheter was advanced via the femoral vein to a position several centimeters above the level of the diaphragm for contrast injection. The femoral artery was cannulated with a No. 10F catheter for arterial pressure monitoring. The right carotid artery was exposed, the distal segment ligated, and a No. 10F basket catheter was advanced to the proximal ascending aorta. This catheter allowed retraction of a centrally placed line to variably distend the distal basket to regulate the degree of aortic regurgitation. A side port of the catheter allowed recording of aortic or left ventricular pressures from the distal end of the catheter. The distal end of the aortic flow probe was exteriorized and connected to an SP 2200 Statham instrument blood flowmeter. After cannulation of the vessels, the dogs received 10,000 U of intravenous heparin and were given 1000 U boluses of heparin per hour to prevent venous or arterial thrombus formation on the catheters. Femoral, central, or left ventricular pressures and the mean and phasic flows were recorded on a direct-writing recorder.

Scanning and experimental protocol. The anesthetized, ventilated dogs were transported to the scanning area. Each dog was positioned on a moveable table, right side down and head directed toward the gantry. The table was skewed 15 degrees left of center to allow the acquisition of short-axis images of the heart. The dogs were connected to an electrocardiographic monitor integrated with the scanner for continuous recording of heart rate. An eight-level localization scan was obtained without contrast before each study to ascertain the position of the left ventricular apex. The table was then adjusted so that the apex was the most caudal point interrogated. A nonionic contrast agent, Iohexol or Iopamidol, was administered by an infusion of 0.75 to 1 ml/kg and at a rate of 1.5 ml/sec for a total injection time of approximately 18 sec for each scan. This ensured opacification of both right and left ventricles throughout scan acquisition. A six- to eight-level scan in cine mode was then obtained to interrogate simultaneously the right and left ventricles. The table was then moved caudally the precise distance interrogated by the first scan and a subsequent four- to six-level scan was acquired to interrogate the remaining portion of the right and left ventricle superior to the portion previously scanned.

ECG-triggered or operator-initiated scanning was performed at 10 to 12 sec after the onset of contrast injection for simultaneous opacification of both ventricles. Duration of scan acquisition ranged from 2.3 sec for a four-level scan to 4.6 sec for an eight-level scan.

Mechanical ventilation was suspended at end-expiration approximately 5 sec before the scan and during the scanning interval to minimize respiratory variation in right and left ventricular stroke volumes. The six dogs were scanned in the control state in the absence of aortic regurgitation. Then variable degrees of aortic regurgitation were induced by manipulation of the basket catheter through the aortic valve. This ranged from one to five studies per dog in the six dogs. After arterial pressure and heart rate had stabilized over the course of 10 to 20 min to ensure hemodynamic equilibrium, scans were then obtained in the presence of aortic regurgitation.

Stoke volume and regurgitant volume measurements. Phasic and mean aortic blood flow from the electromagnetic flow probe were recorded at 50 mm/sec paper speed during the time of scan acquisition. The recording was marked for the exact
duration of scan acquisition. At the conclusion of the experiment dogs were killed. A closed loop across the segment of the proximal aorta containing the electromagnetic flow probe was established. The flow probe was then calibrated in situ by pumping known volumes of the dog’s blood through the closed loop by a pulsatile blood pump and the output of the probe was recorded at 50 mm/sec paper speed. The calibration phasic flows were planimetered and plotted on graph paper as flow in millimeters per second vs the area under the phasic flow tracing in square millimeters. Data were unacceptable for analysis unless the calibration points were linear with the correlation coefficient near 1.0 (.97 to .99) and the regression line passing through 0. Phasic flow recording in vivo showed a marked change from control after the induction of aortic regurgitation (figure 1). The area of the systolic phasic flow deflection above the baseline represented total left ventricular stroke volume. The area of the diastolic negative deflection below the baseline represented the regurgitant volume. These areas were planimetered to obtain the actual volumes. Regurgitant fraction (percent) by electromagnetic flow probe was determined as the ratio of regurgitant volume to total left ventricular stroke volume times 100.

Edge detection criteria used in this experiment for defining the endocardial cavity interface by ultrafast CT have been previously described. 21, 22

End-diastolic and end-systolic frames were chosen from each cine movie spanning the cardiac cycle at that level. End-diastole was visually identified as the frame with the maximal volume (contrast filling) of the left ventricular cavity and corresponded to the onset of the R wave by ECG triggering. End-systole was visually identified as the frame with the smallest volume of the left ventricular cavity, generally three to four frames (150 to 200 msec) after the onset of the R wave. End-diastolic and end-systolic frames of the right ventricle were assumed to be the same frames representing left ventricular end-diastole and end-systole. Left ventricular volumes were planimetered with exclusion of papillary muscles from apex to base. The criteria for identifying the left atrium separate from the left ventricle included systolic expansion and diastolic emptying, the absence of a thick rim of myocardium representative of the ventricle, and a sharply defined tissue plane that separated the left atrial from the left ventricular cavity. Left ventricular volume measurements were discontinued at the level where the aortic valve plane was visualized. The tomographic end-diastolic and end-systolic volume measurements at each level were summated by Simpson’s rule.

CT-derived left ventricular stroke volume was then obtained as a difference between the calculated end-diastolic and end-systolic volumes. 22

The canine right ventricular cavity extends two to three levels (1.5 to 2.5 cm) above the aortic valve plane before the cephalad portion of the right ventricle merges into the proximal aorta and pulmonary artery. The borders of the right ventricle could be readily defined. The septum and right ventricular free wall were easily visualized. The right atrium could be defined and separated from the right ventricle by identification of the tricuspid valve plane and the systolic expansion and diastolic emptying of the right atrium. Separation of the right ventricular outflow tract from the pulmonary artery could be defined as the pulmonary valve plane that could occasionally be seen, as the point where right ventricular contractions ceased to occur, and as the absence of motion that characterized the pulmonary artery throughout the cardiac cycle. The right ventricular end-diastolic and end-systolic frames were chosen for each level and planimetered to derive their respective volumes. The tomographic end-diastolic and end-systolic volumes for each level were summated by Simpson’s rule. CT-derived right ventricular volume was then obtained as a difference between the end-diastolic and end-systolic volumes. 22

CT-derived regurgitant volume was obtained as the difference between the left and right ventricular stroke volumes. The CT-derived regurgitant fraction was obtained as the ratio of the regurgitant volume to left ventricular stroke volume times 100.

Data analysis. Analysis of all data points was achieved by linear regression, least-squares comparison of ultrafast CT-derived measurements to electromagnetic flow probe-derived measurements. The hemodynamic information was presented as the mean ± 1 SD. The interobserver variability was analyzed by linear regression, least-squares comparison between the two observers and encompassed the full range of right and left ventricular stroke volumes, regurgitant volumes, and regurgitant fractions measured.

Results

Left and right ventricular stroke volumes in the control state. The left ventricular stroke volume (range 13 to 50 ml) determined from the proximal aortic electromagnetic flow probe correlated closely to the ultrafast CT-derived left ventricular stroke volume (r = .99, slope = .93, y intercept = 2.23 ml, SEE = 1.2 ml, n = 6). During suspended respiration at end-expiration, the stroke volume determined from the proximal aortic electromagnetic flow probe also correlated closely to the CT-derived right ventricular stroke volume (r = .99, slope = .84, y intercept = 4.23 ml, SEE = 1.09 ml, n = 6). Consequently, the simultaneous right and left ventricular stroke volumes obtained during the control state are remarkably similar (r = 1.0, slope = .91, y intercept = 2.24 ml, SEE = 1.09 ml, n = 6).

Hemodynamic variables before and after the induction of aortic regurgitation. The mean heart rate (115 ± 18 beats/min), mean central aortic pressure (72 ± 9 mm Hg), and mean pulse pressure (55 ± 19 mm Hg) were determined in the control state in the absence of aortic regurgitation in all 16 studies. After the induction of

![EMF Probe cc/sec](image)

**FIGURE 1.** Typical appearance of the change in central aortic pressure (AP) and phasic proximal aorta blood flow obtained by the electromagnetic flow (EMF) probe after the induction of aortic regurgitation. The total left ventricular stroke volume (LVSV) is represented as the positive systolic deflection above the baseline and the regurgitant volume (RgV) as the negative diastolic deflection below the baseline. The planimetered area can be plotted to the linear regression calibration line in figure 1 to derive the actual volumes. AI = onset of aortic regurgitation.
Aortic regurgitation, there was an increase in the mean heart rate (127 ± 28 beats/min), a decrease in the mean central aortic pressure (57 ± 16 mm Hg), and significant widening of the mean pulse pressure (86 ± 24 mm Hg) in the 16 studies.

**Measurement of left ventricular stroke volume in the presence of aortic regurgitation.** The total left ventricular stroke volume determined by the electromagnetic flow probe (range 15.5 to 53.5 ml) correlated closely with the ultrafast CT–derived left ventricular stroke volume despite left ventricular dilatation in the presence of aortic regurgitation (r = .99, slope = .93, y intercept = 4.6 ml, SEE = 1.42 ml, n = 16) (figure 2).

**Measurement of regurgitant volume.** The regurgitant volume determined from the electromagnetic flow probe (range 4.0 to 28.0 ml) correlated closely with the regurgitant volume calculated by ultrafast CT as the difference between left and right ventricular stroke volumes (r = .99, slope = .92, y intercept = 0.98 ml, SEE = 1.02 ml, n = 16) (figure 3).

**Measurement of regurgitant fraction.** The regurgitant fraction calculated as the ratio of electromagnetic flow probe–derived regurgitant volume to total left ventricular stroke volume (range 13% to 53%) correlated closely with the regurgitant fraction calculated from the ratio of ultrafast CT regurgitant volume to total left ventricular stroke volume (r = .94, slope = .98, y intercept = 0.66%, SEE = 4.73%, n = 16) (figure 4).

**Interobserver variability.** The reproducibility of the results by ultrafast CT was assessed by two observers independently selecting the end-diastolic and end-systolic frames and then separately deriving left ventricular stroke volume, right ventricular stroke volume, regurgitant volume, and regurgitant fraction. The studies included in this comparison were selected at random by the second observer.

The interobserver variability was minimal in the measurement of both left ventricular stroke volume (r = .99, slope = .96, y intercept = 1.27 ml, n = 9, range 14.7 to 34.2 ml) and right ventricular stroke volume (r = .99, slope = .92, y intercept = 1.86 ml, n = 9, range 15.9 to 27.9 ml) (figure 5).

The interobserver variability was also minimal in the derivation of the regurgitant volume (r = .95, slope =
1.09, y intercept = .46 ml, n = 7, range 4.3 to 10.4 ml) and the regurgitant fraction (r = .90, slope = .85, y intercept = 4.04%, n = 7, range 13% to 33%) (figure 6).

Discussion

This study demonstrates that experimentally induced aortic regurgitation in dogs can be quantified precisely by ultrafast CT.

Although ultrafast CT has obvious advantages for the evaluation of patients with univalvular regurgitation, it also has several limitations. The instrumentation required is expensive and available in only a small number of centers at present. The patient is exposed to a modest dose of radiation (2.5 to 5.0 rads per study) and a modest volume of nonionic contrast medium that must be injected through a peripheral vein with a power injector. Hence, the patient must fast for 4 hr before the study, have acceptable renal function (creatinine less than 2.0 mg/dl), and be able to tolerate the contrast

FIGURE 5. Interobserver variability is compared for the ultrafast CT measurements of left ventricular stroke volume (LVSV) (left) and of right ventricular stroke volume (RVSV) (right).

FIGURE 6. Interobserver variability is compared for ultrafast CT measurements of regurgitant volume (RgV) (left) and of regurgitant fraction (RgF) (right).
medium. Finally, the measurements can be made accurately only if the cardiac rhythm is regular and the patient can suspend respiration for 5 to 15 sec for data acquisition. Despite these limitations, it is likely that the great majority of patients with isolated aortic regurgitation and some patients with univalvular regurgitation of other valves could be studied effectively with ultrafast CT. Furthermore, the data obtained from an ultrafast CT examination (left ventricular volume,
left ventricular mass,
left and right ventricular systolic function, as well as a precise measure of the volume of regurgitation) are significantly more quantitative than the data that can be obtained by the combined use of other noninvasive imaging techniques such as Doppler two-dimensional echocardiography and radionuclide angiography.

Limitations of current methods in the accurate quantitation of aortic regurgitation. The limitations of the various methods currently used to compare the volume of aortic regurgitation will be briefly reviewed.

Angiography. Angiographic assessment has been a traditional measure of the severity of aortic regurgitation. Arvidsson
and Sandler et al. attempted to quantify regurgitant volume as the difference between biplane angiographic measurement of total left ventricular stroke volume and the effective forward stroke volume determined by either Fick or indicator dye dilution techniques. However, the variability in the correlation between Fick or indicator dye dilution and angiographic stroke volume measurements in the absence of aortic regurgitation are substantial (ranging from 32% to 50% in a series of patients). Abnormal ventricular dimensions in the presence of aortic regurgitation would further compound errors in deriving accurate measurements of left ventricular stroke volume from cineangiographic ventriculograms.

Sellers et al. established a qualitative assessment of aortic regurgitation from aortic root angiography that employed a 1+ to 4+ scale. This scale is dependent on a subjective assessment of the degree of opacification of the left ventricle from regurgitant contrast material. Hunt et al. found a poor correlation between the qualitative severity of aortic regurgitation assessed from an aortographic scale and the quantitative measure of aortic regurgitation derived as the difference between biplane angiographic and indicator dilution stroke volumes (r = .65). This reflects probably both the inaccuracy of the quantitative angiographic measurements as well as the subjective nature of the qualitative aortographic scale.

In summary, although angiography is the traditional standard for the evaluation of the severity of aortic regurgitation, it has major deficiencies in its capacity to quantify regurgitant volume. It is possible that the addition of digital subtraction angiography may improve the accuracy with which aortic regurgitation can be assessed by angiographic methods.

Transcutaneous pulsed Doppler. Investigators have attempted to validate transcutaneous pulsed Doppler as a technique for the noninvasive determination of the severity of aortic regurgitation. From a suprasternal position, the transducer can record aortic blood flow as a positive systolic deflection with forward flow and a negative diastolic deflection with reversal of flow during aortic regurgitation. A measure of the regurgitant fraction is then obtained by planimetry of the areas under each curve. Boughner compared this method favorably to regurgitant volumes derived from angiographic left ventricular stroke volume minus a Fick-derived forward stroke volume (r = .91).

The unfavorable features of this Doppler technique limiting its accuracy are the difficulty in obtaining an adequate suprasternal acoustic window parallel to blood flow in the aorta, the cumbersome nature of data analysis, and forward stroke volume loss to the coronary arteries and right brachiocephalic vessel proximal to the suprasternal Doppler beam.

Doppler 2-D echocardiography. A variety of methods have been analyzed by Doppler two-dimensional echocardiographic techniques in an effort to qualitatively or quantitatively measure the degree of aortic regurgitation with a noninvasive imaging modality.

Diebold et al. determined a regurgitant fraction as the ratio of the maximal amplitude of systolic forward flow to diastolic retrograde flow, whereas Kitabatake et al. derived a regurgitant fraction as the difference between aortic flow volume and pulmonary flow volume. Ciobanu et al. defined the severity of aortic regurgitation qualitatively as the measure of the depth of the regurgitant jet into the left ventricular cavity. Veyrat et al. measured a regurgitant index by mapping the extent of diastolic disturbances in the left ventricular outflow tract generated by aortic regurgitation. The same group also derived an index of the severity of aortic regurgitation as the ratio of regurgitant aortic valvular area to aortic valvular area. Touche et al. measured the aortic regurgitant fraction by a comparison of forward and reverse flows in the aortic arch. Rokey et al. derived regurgitant flow as the difference between aortic outflow (product of the aortic time-velocity integral, aortic annular area, and heart rate) and mitral inflow (product of the mitral time-velocity integral, mitral annular area, and heart rate). Masuyama et al. measured deceleration (slope of the
velocity decline) and half-time index (time of decline to half the peak velocity) as a measure of the severity of aortic regurgitation. These variable methods in defining the degree of aortic regurgitation by twodimensional Doppler echocardiography were correlated to either left ventricular angiography and thermodilution measurements of the regurgitant volume or an aortographic scale of the severity of aortic regurgitation and ranged from \( r = .67 \) to \( r = .94 \).

Despite these many approaches in attempting to derive regurgitant volume or regurgitant fraction, the Doppler echocardiographic system has major methodologic limitations,\(^{18}\) including the calibration of the time interval histogram, electronic noise that causes spectral broadening, pulse repetition frequency failing to detect high-velocity flow, effects of fold-over or aliasing, and difficulty in obtaining a parallel beam to blood flow because of the limited acoustic window. Additionally, the accuracy of these methods is marred in that all of these Doppler echocardiographic studies measuring aortic regurgitation have been validated against conventional approaches in the cardiac catheterization laboratory using ventriculography and thermodilution stroke volumes or aortography, which are flawed and serve as poor "gold standards" of comparison.\(^{4-6}\)

**Radionuclide angiography.** Sorensen et al.\(^ {19}\) derived a radionuclide assessment of regurgitant fraction by R wave synchronous equilibrium angiography that compares the count output between ventricles. Regurgitant fraction by this method correlated with right anterior oblique cineangiography at \( r = .85 \). Manyari et al.\(^ {20}\) compared a similarly derived radionuclide regurgitant fraction with angiography or transcatheter Doppler and found a correlation of \( r = .81 \). However, in 20 control patients without aortic regurgitation the mean regurgitant fraction was 11% rather than 0% and varied between \(-6\%\) and \(34\%\). This indicates considerable unreliability and lack of reproducibility with the radionuclide technique.

Radionuclide angiographic efforts to quantify the severity of aortic regurgitation are adversely affected by the difficulty in separation of ventricular blood pool count activity from contiguous structures, the necessity to subtract variable levels of background activity, and significant errors imposed by attenuation effects.

**Implications.** Quantification of the degree of aortic regurgitation should serve as a better means to assess the potential hemodynamic severity of this lesion. Conventional approaches of current imaging techniques are inadequate in providing a precise quantification of the degree of aortic regurgitation present. However, ultrafast CT is capable of precise and highly reproducible measurements of the regurgitant volume or regurgitant fraction. This can be combined with the previously determined accuracy of left ventricular mass measurements\(^ {21}\) and ventricular volume measurements\(^ {22}\) by ultrafast CT. Consequently, serial assessment of the changes in regurgitant volume, left ventricular mass, or left ventricular volumes can be obtained. It is likely that such data will contribute significantly to the long-term management of patients with univalvular regurgitation.

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