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Background—The lack of a suitable noninvasive method for assessing right ventricular (RV) volume and function has been a major deficiency of two-dimensional (2D) echocardiography. The aim of our animal study was to test a new real-time three-dimensional (3D) echo imaging system for evaluating RV stroke volumes.

Methods and Results—Three to 6 months before hemodynamic and 3D ultrasonic study, the pulmonary valve was excised from 6 sheep (31 to 59 kg) to induce RV volume overload. At the subsequent session, a total of 14 different steady-state hemodynamic conditions were studied. Electromagnetic (EM) flow probes were used for obtaining aortic and pulmonic flows. A unique phased-array volumetric 3D imaging system developed at the Duke University Center for Emerging Cardiovascular Technology was used for ultrasonic imaging. Real-time volumetric images of the RV were digitally stored, and RV stroke volumes were determined by use of parallel slices of the 3D RV data set and subtraction of end-systolic cavity volumes from end-diastolic cavity volumes. Multiple regression analyses showed a good correlation and agreement between the EM-obtained RV stroke volumes (range, 16 to 42 mL/beat) and those obtained by the new real-time 3D method ($r = 0.80$; mean difference, $-2.7 \pm 6.4$ mL/beat).

Conclusions—The real-time 3D system provided good estimation of strictly quantified reference RV stroke volumes, suggesting an important application of this new 3D method. (Circulation. 1998;97:1897-1900.)

Key Words: imaging ■ echocardiography ■ ventricles

Compared with studies of the left ventricle, determining RV volume and function has proved to be challenging for 2D echo methods because of the unique, eccentric, and complicated morphology of the chamber.1–3 3D techniques do not require any assumption about chamber geometry and thus would seem ideal for estimating RV volumes.7,8 Previous ultrasonic 3D studies of RV volume determinations, however, have required cumbersome acquisition and reconstruction techniques, which have limited their clinical applicability.7,8 Recently, a new 3D volume scanning technique has been introduced that requires neither cumbersome acquisition nor gating for ECG and respiration because the 3D imaging is real time.8,10 The aim of the present study was to evaluate the capability of this new real-time 3D ultrasound imaging technique for estimating RV stroke volume in an animal model in which results could be compared with strictly quantified, simultaneously obtained RV stroke volumes determined with an EM flow probes and flow meters.

Methods

Animal Preparations

Three to 6 months before the hemodynamic and 3D ultrasonic study session, the pulmonary valve was surgically excised to induce right ventricular volume overload in 6 sheep weighing 31 to 59 kg. All operative and animal management procedures were approved by the National Heart, Lung, and Blood Institute.11,12

EM Flow Probe and Meter Methods

During the experimental session, the animals underwent repeat thoracotomy under general anesthesia with 2% isoflurane with oxygen. An EM flow probe (model EP455, Carolina Medical Electronics, Inc) was placed snugly around the pulmonary artery just above the pulmonary valve sinuses, and another EM flow probe was placed around the skeletonized ascending aorta distal to the coronary ostia. The baseline for the pulmonary EM flow recording was adjusted until the forward minus the backward flow volume equaled the aortic EM forward flow volume. After baseline measurements, varying RV forward stroke volumes and pulmonary regurgitant volumes were produced by altering preload and/or afterload by use
of blood transfusion and angiotensin II (Peptide Institute Inc, provided by Tanabe Seiyaku Co).

**3D Method for Imaging the RV Chamber**

A newly developed phased-array real-time volumetric 3D imaging system was used in this study. The system was developed in the Duke University Center for Emerging Cardiovascular Technology and is currently operated with 2.5- or 3.4-MHz transducers (both 14 mm in diameter). A 2D array and the pyramid-shaped volumetric scan are shown schematically in Figure 1A. The 2D arrays were composed of 43×43 square elements, each measuring 0.3×0.3 mm. The volume was scanned rapidly with 16-to-1 parallel processing in the receive system. A broad transmit beam was used to encompass the 16 simultaneous receive directions, as indicated in Figure 1A. Consequently, the overall scanned pyramidal volume was composed of 256 small pyramids stacked side by side. This scheme is indicated in Figure 1A, in which, for simplification, the scan volume is composed of a 6×6 matrix of small pyramids. In actual scanning, a 16×16 volume was used to scan over a 64°×64° volume. Each small pyramid was in turn defined by the 4×4 matrix of “receive directions” and measured 4° on each side. Image display consisted of 2 independent B-mode and 2 or 3 C-mode scan images simultaneously in variable orientations. A typical C-scan is also shown in Figure 1A. C-scans are planes parallel to the transducer face and cannot be imaged in real time by conventional ultrasound systems. Standard B-scans, which originated at the center of the transducer aperture, could be produced in any direction within the volume. The system scanned at speeds of 18 to 40 volumes per second as determined by the maximal depth range. The RV was imaged with the transducer directly on the apex of the left ventricle. In this way, the left ventricle was used as a standoff to permit imaging of the entire RV. Three seconds of real-time volumetric data of the RV was digitally stored in memory and on disk after image quality was maximized for each data set. The original concept and a detailed technical description of this real-time 3D system, including the “C” scan imaging using parallel processing, have been reported previously.13,14

**RV Volume Measurement**

C-mode scan images selected from the volume data were used for measuring RV volumes in both end diastole and end systole. The ECG was recorded at the time of real-time 3D imaging. The QRS wave was used for selecting the largest RV volume, ie, the end-diastolic RV volume, and the T wave for selecting the smallest RV volume, ie, the end-systolic RV volume. Parallel sections (slice thickness ranged from 4 to 9 mm) of the RV from the apex through the plane that included both RV inflow and outflow/pulmonary valve were developed. The cavity of the RV, including the RV outflow tract, in each section (Figure 1B) was manually traced and cavity area calculated in a standard way with the 3D system software. Occasionally, a portion of the RV cavity outline was outside the 64° pyramid in 1 or 2 C-scans during diastole. With the full 3D data, however, the outline could easily be extrapolated from the adjacent planes. 2D cavity areas, each multiplied by the section thickness, were added consecutively every 5 mm along the long axis of the RV to obtain RV cavity volume. For each hemodynamic condition, both diastolic and systolic RV volumes were determined and RV systolic stroke volume was obtained by subtracting end-diastolic volume from end-diastolic volume. For area tracing, RV trabeculations and moderator band structures were excluded from RV cavity contours.

**Interobserver Variability**

To evaluate the effect of variability on the 3D measurement of RV systolic volumes, 8 hemodynamic conditions were randomly selected. Two independent observers performed the 3D measurements of RV stroke volumes, each without knowledge of the results obtained by the other observer or the flowmeter data.

**Statistics**

Data are presented as mean±SD for descriptive statistics. Because multiple points were used in the same sheep, the relationship between the real-time 3D method versus the EM flowmeter method was analyzed by multiple regression analyses.15,16 To assess agree-
ment and predictability between RV systolic volumes by 3D and those by the reference flowmeter technique, the method of Bland and Altman was used. Statistical significance was defined as a value of $P < 0.05$.

**Results**

RV stroke volumes obtained by the EM flowmeter method ranged from 16 to 42 mL/beat. Heart rates ranged from 89 to 143 bpm. Pulmonary regurgitant volumes ranged from 0.6 to 25 mL/beat, and regurgitant fraction ranged from 4% to 58%.

**RV Stroke Volume Measurement**

Multiple regression analyses showed a good correlation between the EM-derived RV stroke volumes and those obtained by the new real-time 3D method ($r=0.80$, Figure 2A). The method of Bland and Altman demonstrated a good agreement between them (mean difference, $-2.7\pm6.4$ mL/beat; Figure 2B).

**Interobserver Variability**

There was good agreement between 2 independent observers’ measurements of RV systolic volumes ($r=0.87$, $P<0.001$; mean difference, $-0.53\pm5.5$ mL/beat).

**Discussion**

In this study, the application of the new real-time 3D system not only demonstrated unique 3D imaging capabilities but also provided good estimates of RV stroke volumes (obtained by subtracting end-systolic RV cavity volumes from the end-diastolic RV volumes).

**Previous Echo Studies Estimating RV Volumes**

Measurements of RV volumes by 2D ultrasound imaging techniques have been attempted with monoplane/biplane area-length methods. Jiang et al validated a 3D ultrasound method for estimating RV volume by use of a sophisticated in vivo model for providing reference RV volume. More recently, a commercially available 3D system has been introduced that is capable of reconstructing cardiac chambers and valves and quantifying left ventricular volumes. However, use of this 3D system is time intensive, requiring 2 to 4 minutes to acquire a 3D data set and >15 minutes to reconstruct 3D images properly. MRI techniques have also been used for measuring RV volumes. Instrument cost, the space required for MRI systems, and their lack of portability have limited routine clinical application of MRI for evaluating RV volume.

**Advantages of the New Real-time 3D Method**

Compared with the above-mentioned 3D methods, this new real-time volumetric 3D ultrasound technique has retained many of the advantages of 2D echocardiography for clinical applications in that on-line adjustment of conventional echocardiographic planes is used for acquiring adequate-quality 3D data sets. Breath-holding and gating for ECG and/or respiration are not required for this new method.

**Limitations**

In our in vivo study, we could not compare absolute 3D RV end-diastolic and end-systolic cavity volume directly with a volume reference standard. There was, however, good agreement between the 3D RV stroke volumes calculated as the end-diastolic minus end-systolic 3D cavity volumes and those by the EM flowmeter over a wide range of values. In our method for determination of RV stroke volume, the variability of end-systolic and end-diastolic RV volume measurements may be additive, because their difference was used to determine stroke volumes for comparison with the EM flow data. At present, spatial resolution and, thereby, border detection with this technology is limited by the number of elements and channels available in the system. The $64^\circ$ angle and its consequent limited pyramidal volume can make it difficult to include full cavity contours in the volume of scanning, especially for dilated hearts. Other problems, such as unsatisfactory imaging windows in some patients, will also need to be evaluated in future clinical studies. Continued development of ultrasound scanner and transducer technolo-
gories necessary to support volume scanning, however, should progressively ameliorate these limitations.

Conclusions
Real-time 3D ultrasound imaging provides good estimates of RV stroke volumes. This suggests potential clinical applicability of this new 3D method for fulfilling an important function in noninvasive evaluation of heart disease.

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