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3D Echocardiography to Evaluate Right Atrial Pressure in Acutely Decompensated Heart Failure

Correlation With Invasive Hemodynamics

Ayan R. Patel, MD,*† Alawi A. Alsheikh-Ali, MD, MS,‡§ Jayanta Mukherjee, MD,* Antonietta Evangelista, MD,* Dima Quraini, MD,* Linda J. Ordway, MS, ACNP-BC,† Jeffrey T. Kuvin, MD,* David DeNofrio, MD,† Natesa G. Pandian, MD*

Boston, Massachusetts; and Abu Dhabi, United Arab Emirates

OBJECTIVES This study examined the utility of 3-dimensional right atrial volume index (3D-RAVi), combined with 2-dimensional echocardiographic (2DE) parameters, for the identification of elevated right atrial pressure (RAP) in patients with heart failure.

BACKGROUND Accurate noninvasive determination of RAP is clinically important for the management of patients with heart failure. Although 2DE methods have been used to noninvasively estimate RAP, the accuracy of these parameters has limitations when estimating RAP in an individual patient. Three-dimensional echocardiography (3DE) provides tomographic imaging of right atrial volume that may be helpful in refining the noninvasive assessment of hemodynamics in patients with heart failure.

METHODS 2DE and 3DE studies were examined in 40 initial patients who were admitted for acutely decompensated heart failure. Simultaneous pulmonary artery catheter monitoring was performed. The relationship between echocardiographic parameters and RAP was examined in this derivation group. The findings from the derivation group were then prospectively tested in a validation group of 40 additional patients.

RESULTS Mean RAP was 11 ± 5 mm Hg (range 2 to 22 mm Hg). 3D-RAVi correlated with RAP ($r = 0.51$, $p < 0.001$), whereas 2-dimensional right atrial volume index did not. Inferior vena cava (IVC) diameter ≥2 cm and IVC respirophasic collapse <40% also correlated with RAP ($p < 0.001$ and $p = 0.028$, respectively). Based on receiver-operator characteristic curve analysis, 3D-RAVi ≥35 ml/m^2 was the optimal 3D-RAVi cutpoint for identifying RAP >10 mm Hg. The value of 3D-RAVi ≥35 ml/m^2, combined with IVC measures, for predicting RAP >10 mm Hg was prospectively tested in the validation group. 3D-RAVi ≥35 ml/m^2 in combination with IVC ≥2 cm had a high accuracy (88%) for identifying RAP >10 mm Hg and had a higher accuracy than the combination of IVC ≥2 cm and IVC collapse <40% (accuracy: 68%, $p = 0.038$).

CONCLUSIONS In patients with heart failure, 3D-RAVi in conjunction with IVC parameters has a high accuracy for detection of elevated RAP. The addition of 3D-RAVi to 2DE methods may be helpful in the noninvasive estimation of right atrial pressure. (J Am Coll Cardiol Img 2011;4:938–45) © 2011 by the American College of Cardiology Foundation

From the *Cardiovascular Imaging and Hemodynamic Laboratory, Tufts Medical Center, Boston, Massachusetts; †Heart Failure and Cardiac Transplant Center, Tufts Medical Center, Boston, Massachusetts; ‡Institute for Clinical Research and Health Policy Studies, Tufts Medical Center, Boston, Massachusetts; and the §Institute of Cardiac Sciences, Sheikh Khalifa Medical City, Abu Dhabi, United Arab Emirates. The laboratory where this research was conducted has received an equipment grant from Philips Healthcare. The authors have reported that they have no relationships relevant to the contents of this paper to disclose.

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The accurate noninvasive assessment of right atrial pressure (RAP) has important implications for the management of patients with heart failure. The correct estimation of RAP is critical for the accurate echocardiographic assessment of right ventricular systolic pressures. Furthermore, accurate assessment of RAP provides important information for the management of the patient's volume status. RAP is commonly estimated by 2-dimensional echocardiographic (2DE) parameters, such as the presence of inferior vena cava (IVC) dilation and the degree of inspiratory IVC collapse (1–6). However, the reliability of IVC parameters has varied in prior studies (1–4,6–8).

There is a paucity of data regarding the utility of right atrial size for estimating RAP, and the investigation of the value of right atrial size for assessing hemodynamics has been limited by the lack of reliable 2DE methods for assessing the right atrium. The subjectivity of qualitative assessment of RA size inherently presents potential limitations to the accuracy of this method, and quantitation of RA size by 2-dimensional echocardiography may not provide an accurate measure of true chamber size due to the use of only 1 imaging plane, as well as potential errors introduced by foreshortening of the imaging plane. Additionally, in patients with heart failure, the geometric assumptions involved with 2DE analysis may be less accurate if the RA shape is distorted as the chamber enlarges. Three-dimensional echocardiography (3DE) provides tomographic imaging of cardiac chambers, thereby avoiding some of these technical limitations, and 3DE-derived RA volume measurements have previously been validated with cardiac magnetic resonance (9). The multiple imaging planes afforded by 3DE provide a more accurate assessment of RA size and, therefore, provide an opportunity to assess whether RA size can provide information regarding RA filling pressures. The purpose of this study was to examine the utility of 3DE-derived RA volume for identification of elevated RAP in patients with acutely decompensated heart failure, in whom the evaluation of RAP has important clinical relevance.

METHODS

2DE, Doppler, and 3DE studies were obtained and analyzed in consecutive patients with advanced chronic heart failure who were admitted to the Heart Failure and Cardiac Transplant Service at Tufts Medical Center for acutely decompensated heart failure and who underwent pulmonary artery catheter hemodynamic monitoring during the hospitalization. Hemodynamic measurements were obtained at end-expiration, using an average over 2 end-expiratory cycles, by an observer who was blinded to the echocardiographic data. An initial group of patients was examined as a derivation group to assess the relationship between echocardiographic parameters and RAP, and a second validation group was then examined to prospectively test the findings from the derivation group. The study was approved by the Tufts Medical Center Institutional Review Board. Patients with inadequate 3DE images were excluded from the study. Invasive hemodynamic measurements were obtained immediately following the echocardiographic studies.

Echocardiographic methods. Echocardiographic measurements were performed by a reader who was blinded to the invasive hemodynamic data. The following 2DE and Doppler parameters were examined: qualitative RA size, 2-dimensional right atrial volume index (2D-RAVi), 2DE RA planimetry-derived area, 2DE RA minor axis and major axis diameters (from apical 4-chamber view), IVC diameter, IVC percentage of respirophasic collapse, tricuspid inflow E- and A-wave velocities, tricuspid inflow E-wave deceleration time, and tricuspid annular tissue Doppler early diastolic velocity (from the right ventricular free wall annulus). Tricuspid E/E′ was calculated as the ratio of tricuspid inflow E-wave velocity and tricuspid annular tissue Doppler early diastolic velocity. 2DE measurements were obtained from a single cardiac cycle, using standard methods (10). Doppler recordings were performed in accordance with standard echocardiographic methods and were obtained from an average of 5 cardiac cycles (11). Tricuspid valve E/A ratios were calculated in patients who were in sinus rhythm and who had distinctly identifiable E and A waves. Qualitative RA size was scaled from 0 to 3 (0 = no enlargement, 1 = mild enlargement, 2 = moderate enlargement, and 3 = severe enlargement). Qualitative RA size was determined by a reader who was blinded to the quantitative measures. The IVC diameter was measured from 2DE images, approximately 2 cm from the junction of the right atrium. The maximal and minimal IVC diameters during the respiratory cycle, with sniff test, were measured to calculate respirophasic IVC collapse.

ABBREVIATIONS AND ACRONYMS

2DE = two-dimensional echocardiography

2D-RAVi = 2-dimensional right atrial volume index

3DE = 3-dimensional echocardiography

3D-RAVi = 3-dimensional right atrial volume index

AUC = area under the curve

IVC = inferior vena cava

RA = right atrial

RAP = right atrial pressure(s)

ROC = receiver-operator characteristic

The IVC was considered to be dilated if the diameter was ≥2 cm (3). Normal IVC collapse was considered present if there was at least 40% reduction in IVC size during the inspiratory phase of respiration (3). 2DE maximal RA volume was calculated by Simpson method in the apical 4-chamber view (7,10,12). A full-volume real-time 3DE acquisition of the right atrium was obtained in the apical 4-chamber view, using electrocardiogram gating over 4 cardiac cycles (iE33 system/X3-1 transducer, Philips Healthcare, Best, the Netherlands). The 3DE maximal RA volume was measured on an offline analysis system (4D Cardio-View, TomTec Imaging, Unterschleissheim, Germany) by manually tracing the RA endocardial border in 8 equiangular longitudinal-axis planes at ventricular end-systole (Fig. 1). Ventricular end-systole was identified as the frame before tricuspid valve opening. Intraobserver variability for 3DE RA volume was calculated from repeat measurements of 10 randomly selected subjects, and interobserver variability was calculated from analysis of 3DE RA volumes in the same subjects by a second investigator. The RA volumes were indexed to body surface area to yield indexed 2DE and 3DE RA volumes (2D-RAVi and 3D-RAVi, respectively).

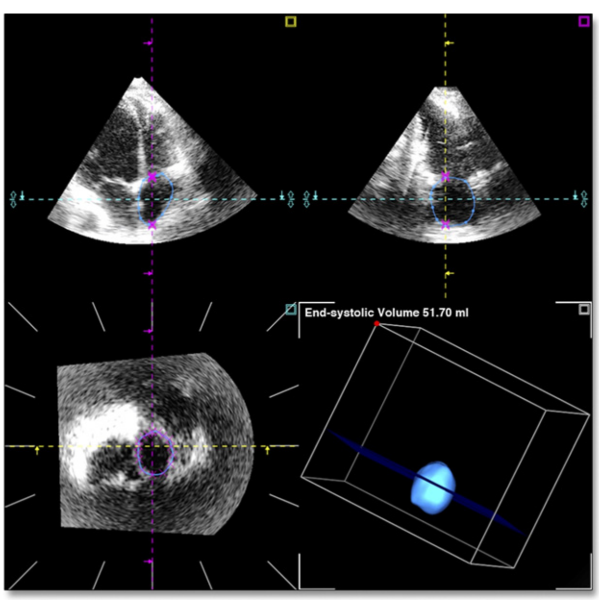

Figure 1. **3DE Analysis of RA Volume**

Multiple equiangular longitudinal-axis planes are generated (as indicated in **lower left panel**) and the right atrial (RA) endocardial border is manually traced in each pair of orthogonal planes **(upper panels)**, resulting in a RA volume calculation **(lower right panel)**. 3DE = 3-dimensional echocardiography.

Statistical analysis. Continuous variables are presented as mean ± SD. Univariate regression analysis was used to examine associations between individual echocardiographic parameters and mean RAP (SigmaStat, version 2.03, Aspire Software International, Ashburn, Virginia). Receiver-operator characteristic (ROC) curves for 2DE and 3DE variables were examined, and optimal cutpoints were determined from those ROC curves with statistically significant discriminatory power (MedCalc 11.3.8, MedCalc Software, Mariakerke, Belgium). Optimal cutpoints from ROC curve analyses were determined from the shortest distance from the upper left of the ROC plot. Comparison of ROC curves was performed using the method of DeLong and DeLong (13). The sensitivity, specificity, and accuracy for various parameters to detect elevated RAP were determined for prediction of mean RAP >10 mm Hg. Intraclass correlation coefficients were calculated to examine intraobserver and interobserver variability.

RESULTS

Patient characteristics. Of 98 total patients screened for the study (for the derivation group and the validation group), 80 (82%) had 3DE studies that were of sufficient quality for 3DE RA volume analysis. In the initial group of 40 subjects, the mean RA pressure was 11 ± 5 mm Hg (range 2 to 22 mm Hg) and the mean left ventricular ejection fraction was 22 ± 15%. Eighteen patients (45%) had RA pressures >10 mm Hg, and 8 patients (20%) had RA pressures >15 mm Hg. Ten patients (25%) were in atrial fibrillation. Additional baseline characteristics of this derivation group study population are shown in Table 1. No patients were receiving mechanical ventilation at the time of the study. Fifty percent of subjects had tricuspid regurgitation (22% mild tricuspid regurgitation, 20% moderate tricuspid regurgitation, 8% severe tricuspid regurgitation).

Doppler measures and RAP. Consistent with prior observations, tricuspid E/A ratio correlated significantly with RAP (r = 0.571, p = 0.017). However, E/A ratio could only be determined in 43% of patients and was not possible in the others due to the absence of sinus rhythm (n = 10), presence of tricuspid valve annuloplasty ring (n = 1), or inadequate image quality (n = 12) due to tachycardia. Tricuspid E′ (right ventricular free wall annulus) did not correlate with RAP (r = 0.31, p = 0.068),

Table 1. Baseline Characteristics of the Derivation Group

Age, yrs	53.1 ± 12.3 (26–76)
Sex, male/female	27/13
%LVEF	22.4 ± 14.6 (5–65)
Mean RAP, mm Hg	10.8 ± 5.1 (2–22)
PA diastolic pressure, mm Hg	25.9 ± 8.7 (12–47)
PA systolic pressure, mm Hg	51.1 ± 16.7 (19–98)
PA mean, mm Hg	34.7 ± 11.2 (15–68)
IVC, cm	1.7 ± 0.5 (0.9–2.6)
IVC collapse, %	46 ± 26 (0–100)
Tricuspid E/A	1.2 ± 0.5 (0.7–2.3)
Tricuspid deceleration time, ms	168 ± 92 (60–390)
Tricuspid E/E'_{RV}	8 ± 5 (3–27)
3D RA maximum volume index, ml/m^2	40.5 ± 17.6 (13.7–79.9)
2D RA maximum volume index, ml/m^2	35.2 ± 15.6 (14.8–69.0)

Values are mean ± SD (range) or n.
2D = 2-dimensional; 3D = 3-dimensional; A = peak atrial tricuspid inflow velocity; E = peak early diastolic tricuspid inflow velocity; E'_{RV} = right ventricular annular early diastolic velocity; IVC = inferior vena cava; LVEF = left ventricular ejection fraction; PA = pulmonary artery; RA = right atrium; RAP = right atrial pressure.

nor did tricuspid E/E′ ($r = 0.09$, $p = 0.612$). In addition, tricuspid E-wave deceleration time did not correlate significantly with RAP in this population ($r = -0.38$, $p = 0.057$).

RA size and RA pressure. 2D-RAVi correlated modestly with 3D-RAVi ($r = 0.582$, $p < 0.001$). Qualitative assessment of RA size was weakly correlated with 3D-RAVi ($r = 0.427$, $p = 0.006$). Correlations between RAP and 2DE parameters are shown in Table 2. Both IVC ≥2 cm ($p < 0.001$) and IVC respirophasic collapse <40% ($p = 0.028$) were correlated with RAP. 2D RA area, 2D RA minor axis diameter, and 2D RA major axis diameter were not significantly correlated with RAP. RA maximal volume index derived by 3DE correlated with RAP ($r = 0.51$, $p < 0.001$), whereas neither 2D-RAVi nor qualitative assessment of RA size was significantly associated with RAP. Acquisition of 3DE images could be performed within 1 min, and calculation of 3DE RA volume required approximately 5 min. Analysis of 3DE RA volume intraobserver variability demonstrated an intraclass correlation coefficient of 0.94 and analysis of interobserver variability yielded an intraclass correlation coefficient of 0.898.

ROC curve analysis of 2DE parameters for identification of RAP >10 mm Hg was performed (Table 2). The ROC curves for 2D-RAVi and 3D-RAVi for detection of RAP >10 mm Hg are shown in Figures 2A and 2B. The area under the curve (AUC) of 2D-RAVi for detection of RAP >10 mmHg was not statistically significant and demonstrated poor discriminatory ability to identify elevated RAP (AUC = 0.626, $p = 0.209$). The AUC of 3D-RAVi for identification of RAP >10 mm Hg was 0.775 ($p = 0.0006$), which was significantly higher than that of 2D-RAVi ($p = 0.02$). Based on ROC curve analysis, the idealized cutpoint for 3D-RAVi for detection of RAP >10 mm Hg was a 3D-RAVi ≥35 ml/m^2.

Prediction of RAP in the validation group. In order to test the utility of 3D-RAVi ≥35 ml/m^2 in combination with IVC parameters for detecting elevated RAP, this parameter was prospectively tested in a group of 40 additional patients who were admitted with acutely decompensated heart failure. The inclusion criteria were the same as that of the initial derivation group. Mean RAP in the validation group was 13 ± 5 mm Hg (range 1 to 24 mm Hg) and mean 3D-RAVi was 43 ± 21 ml/m^2 (range 12 to 108 ml/m^2). The 3D-RAVi parameters that were tested included: 1) 3D-RAVi ≥35 ml/m^2 in conjunction with IVC ≥2 cm (positive if both elements were present); 2) 3D-RAVi ≥35 ml/m^2 alone; and 3) 3D-RAVi ≥35 ml/m^2 combined with IVC ≥2 cm and IVC respirophasic collapse <40% (positive

Table 2. Correlation Between 2DE/3DE Parameters and RAP, and ROC Curve Analysis for Identifying RAP >10 mm Hg (Derivation Group)

	r Value	p Value	AUC (for RAP >10 mm Hg)	p Value	Optimal Cutpoint Value
3D-RAVi, ml/m^2, n = 40	0.51	<0.001	0.775	0.0006	≥35 ml/m^2
2D-RAVi, ml/m^2, n = 40	0.25	0.160	0.626	0.21	—
2D RA area, cm^2, n = 40	0.13	0.355	0.628	0.20	—
2D major-axis RA diameter, cm, n = 40	0.07	0.706	0.520	0.85	—
2D minor-axis RA diameter, cm, n = 40	0.32	0.076	0.665	0.09	—
Qualitative RA size, scale 0–3, n = 40	0.29	0.071	0.631	0.14	—
IVC diameter, cm, n = 36	0.56	<0.001	0.756	0.0068	≥2 cm
IVC % respirophasic collapse, n = 34	−0.49	0.006	0.673	0.09	—

Dashes indicate that an optimal cutpoint value could not be determined.
AUC = area under the curve; 2DE = 2-dimensional echocardiography; 3DE = 3-dimensional echocardiography; RAVi = right atrial volume index; ROC = receiver-operator characteristic; other abbreviations as in Table 1.

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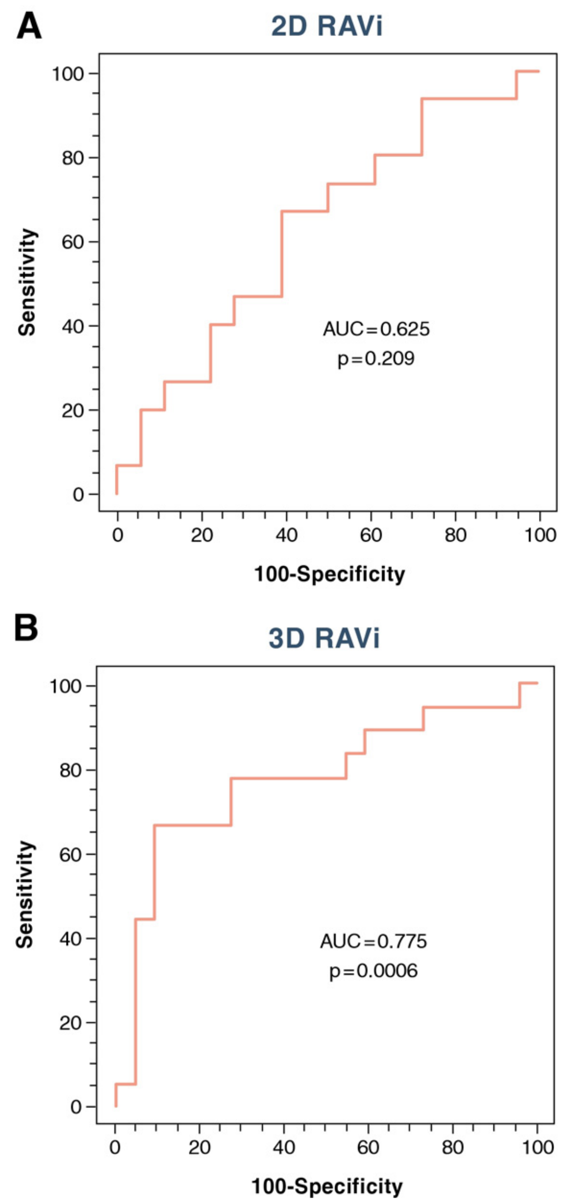

Figure 2. RAVi ROC Curves

(A) Receiver-operator characteristic (ROC) curve of 2-dimensional right atrial volume index (2D-RAVi) for identification of right atrial pressure >10 mm Hg. **(B)** ROC curve of 3-dimensional right atrial volume index (3D-RAVi) for identification of right atrial pressure >10 mm Hg. AUC = area under the curve.

if all 3 elements were present). The sensitivity, specificity, and accuracy of these parameters for detection of RAP >10 mm Hg in the validation group are shown in Table 3. Of the 3D-RAVi parameters that were examined, the combination of RAVI ≥35 ml/m^2 and dilated IVC (IVC ≥2 cm) yielded the most optimal balance between sensitivity and specificity. For prediction of RAP >10 mm Hg, the presence of both 3D-RAVi ≥35 ml/m^2 and a dilated IVC had a sensitivity of 86%, specificity of 92%, and accuracy of 88% in the validation group. The combination of 3D-RAVi ≥35 ml/m^2 and IVC ≥2 cm had a higher sensitivity and accuracy for RAP >10 mm Hg than did the combination of dilated IVC with reduced IVC respirophasic collapse. Compared with IVC ≥2 cm alone, 3D-RAVi ≥35 ml/m^2 combined with IVC ≥2 cm trended toward a higher specificity for RAP >10 mm Hg ($p = 0.159$) in the validation group. For detection of RAP >15 mm Hg in the validation group, the presence of IVC ≥2 cm and IVC collapse <40% had a sensitivity of 86%, specificity of 73%, and accuracy of 78%, whereas the combination of 3D-RAVi ≥35 ml/m^2 with the presence of both IVC ≥2 cm and IVC collapse <40% had a sensitivity of 86%, specificity of 85%, and accuracy of 85% (p = NS).

DISCUSSION

This is the first study to examine the utility of 3DE for noninvasive identification of elevated RAP, testing the concept that enlarged 3DE-derived RA volume may be useful for identifying elevated RAP. Although qualitative and 2DE measures of RA size did not correlate with RAP, 3DE RA volume was correlated with RAP in this population of advanced heart failure patients. Compared with the combination of dilated IVC and reduced IVC collapse, the addition of 3DE maximal RA volume to IVC diameter resulted in improved sensitivity for identification of RAP >10 mm Hg. The combination of 3D-RAVi ≥35 ml/m^2 and IVC ≥2 cm, compared with the presence of a dilated IVC alone, also trended toward improved specificity for RAP >10 mm Hg without compromising accuracy or sensitivity.

Whereas RA size is determined by qualitative assessment in many laboratories, the results of the current study indicate only a modest correlation between qualitative assessment of RA size and 3DE RA volume. In addition, whereas 3DE RA volume correlated with RAP, neither qualitative assessment of RA size nor quantitative 2DE RA volume correlated with RAP. The finding that 2DE assessment of RA size correlates only modestly with 3DE measurements is consistent with previous observations (14,15). The lack of a strong correlation between 2DE RA volume and 3DE RA volume may be due to foreshortening of 2DE images, as well as errors introduced by the

Table 3. Accuracy, Sensitivity, and Specificity of Echocardiographic Measurements for Identification of RAP >10 mm Hg in the Validation Group (n = 40)

	3D-RAVi ≥35 ml/m² + IVC ≥2 cm	3D-RAVi ≥35 ml/m²	3D-RAVi ≥35 ml/m² + IVC ≥2 cm + IVCC <40%	IVC ≥2 cm	IVC ≥2 cm + IVCC <40%
Accuracy	0.88*	0.85	0.70	0.83	0.68
Sensitivity	0.86†	0.89	0.57	0.89	0.60
Specificity	0.92	0.75	1.00	0.67	0.83

Comparison of 3D-RAVi ≥35 ml/m² + IVC ≥2 cm versus IVC parameters alone: *p = 0.038 versus IVC ≥2 cm + IVCC <40%; †p = 0.041 versus IVC ≥2 cm + IVCC <40%.
IVCC = inferior vena cava respirophasic collapse; other abbreviations as in Tables 1 and 2.

geometric assumptions used in 2DE analysis. A prior study examining the relationship between 2DE and 3DE measures of left atrial size also observed only a modest correlation between unidimensional measures of atrial size, 2DE left atrial volume, and 3DE left atrial volume (14). Similarly, only modest correlations have previously been observed between 3DE RA volume and 2D or unidimensional measures of RA size (15). Interestingly, other investigators have observed a correlation between RA long- and short-axis diameters and RAP in patients with heart failure (16). The current study examined patients with advanced heart failure, in whom RA enlargement may be more prominent and may occur in a more asymmetric fashion, thereby limiting the utility of unidimensional and single-plane 2DE measurements. Our findings are consistent, however, with the prior observation that increasing RA size is associated with higher RAP in patients with heart failure. The current study expands on these observations by identifying a single-measure, 3DE RA volume, which incorporates these multiple planes into a simplified, more accurate assessment of RA size.

Our observations regarding the relationship of IVC and Doppler parameters with RAP are consistent with those reported in prior studies (3,7). As reported by previous investigators (7), the current study found a significant relation between tricuspid E/A ratio and RAP. However, as expected in an acutely decompensated heart failure population, a sizable proportion of subjects in our study were in atrial fibrillation or were tachycardic, thereby limiting the ability to use this parameter in many patients. Although 3DE imaging may be technically difficult in patients who have atrial fibrillation with rapid ventricular rates or highly irregular R-R intervals, we found that 3DE acquisition and analysis of RA volume was feasible in patients with rate-controlled atrial fibrillation. Similarly, other studies have previously reported on the use of 3DE imaging for assessment of atrial volumes in patients with atrial fibrillation (15,17,18).

In the current study as well as many others, IVC diameter and respirophasic collapse have been demonstrated to significantly correlate with RAP. Our finding of an optimal IVC diameter cutpoint of ≥2 cm for detection of elevated RAP is consistent with prior observations (3). We observed that dilated IVC with reduced IVC inspiratory collapse had good specificity for detection of RAP >10 mm Hg, but lower sensitivity. These findings may, in part, be related to technical challenges of performing IVC imaging in patients who are tachypneic, particularly in the decompensated heart failure population. Additionally, difficulties in standardization of the inspiratory effort may introduce a source of error when using IVC parameters alone to categorize RAP. Thus, even though correlations are observed between RAP and several 2DE and Doppler measures, each of these parameters has some limitations. Increased RA volume is likely the result of chronically elevated RAP and, thus, may not be reflective of acute changes in RAP. However, the presence of increased RA volume in conjunction with IVC evidence of increased RAP appears to provide greater overall accuracy for identifying elevated RAP than IVC parameters alone. Thus, the emergence of newer echocardiographic techniques, such as 3DE, may provide the opportunity to further refine methods for noninvasively assessing RAP.

Study limitations. Three-dimensional analysis of RA volume was not feasible in 18% of acutely decompensated heart failure patients, demonstrating the current limitations of 3DE imaging in patients with technically difficult echocardiographic windows. Another limitation is the additional time (~6 min) required for 3D imaging and RA volume measurement. Because the optimal number of planes required for accurate measurement of 3DE RAV has not been established, we chose to calculate RA volume from analysis of 8 equiangular planes, in order to minimize error in the measurements. However, it is possible that a lesser number of planes will be sufficient to quantitate RA volume, thereby simplifying the methodology and reducing the amount of time required for analysis. Further investigation of the optimal number of planes for accurate calculation of RA volume is an area that will benefit from future investigation. Although the results of the current study are promising, further simplification of 3DE quantification will be important for potential utilization of such methods in clinical practice.

It should also be noted that the findings of this study are limited to a population of patients with acutely decompensated advanced heart failure. The relationship between echocardiographic parameters and hemodynamics may be altered in patients with chronic heart failure, in whom chronically elevated pressures may affect RA size or IVC size. We aimed to examine the relationship between these echocardiographic parameters and hemodynamics specifically in the acutely decompensated advanced heart failure population, in whom the accurate noninvasive assessment of hemodynamics is highly relevant from a clinical standpoint. This is the first study to examine the utility of 3DE-derived measurements to estimate RAP, and additional study in a larger population of patients will be helpful to further validate and expand on the findings of the current study.

CONCLUSIONS

The use of traditional 2DE parameters for the estimation of RAP has limitations that may be improved by the incorporation of newer echocardiographic techniques, such as 3DE. In patients with acutely decompensated heart failure, the use of 3DE RA volume in conjunction with IVC diameter has a high accuracy for detection of elevated RAP and has the potential to help refine echocardiographic methods for estimation of RAP.

Reprint requests and correspondence: Dr. Ayan R. Patel, Cardiovascular Imaging and Hemodynamic Laboratory, Tufts Medical Center, 800 Washington Street, Box 32, Boston, Massachusetts 02111. *E-mail: apatel@tuftsmedicalcenter.org*.

REFERENCES

1. Kircher BJ, Himelman RB, Schiller NB. Noninvasive estimation of right atrial pressure from the inspiratory collapse of the inferior vena cava. Am J Cardiol 1990;66:493–6.
2. Mintz GS, Kotler MN, Parry WR, Iskandrian AS, Kane SA. Real-time inferior vena caval ultrasonography: normal and abnormal findings and its use in assessing right-heart function. Circulation 1982;64:1018–25.
3. Brennan JM, Blair JE, Goonwardena S, et al. Reappraisal of the use of inferior vena cava for estimating right atrial pressure. J Am Soc Echocardiogr 2007;20:857–61.
4. Brennan JM, Blair JE, Goonwardena S, et al. A comparison by medical residents of physical examination versus hand-carried ultrasound for estimating right atrial pressure. Am J Cardiol 2007;99:1614–6.
5. Ommen SR, Nishimura RA, Hurrell DG, Klarich KW. Assessment of right atrial pressure with 2-dimensional and Doppler echocardiography: a simultaneous catheterization and echocardiographic study. Mayo Clin Proc 2000;75:24–9.
6. Vourvouri EC, Schinkel AF, Roelandt JR, et al. Screening for left ventricular dysfunction using a hand-carried cardiac ultrasound device. Eur J Heart Fail 2003;5:767–74.
7. Nagueh SF, Kopelen HA, Zoghbi WA. Relation of mean right atrial pressure to echocardiographic and Doppler parameters of right atrial and right ventricular function. Circulation 1996;93:1160–9.
8. Moreno FL, Hagan AD, Homen JR, Pryor TA, Strickland RD, Castle CH. Evaluation of size and dynamics of the inferior vena cava as an index of right-sided cardiac function. Am J Cardiol 1984;53:579–85.
9. Keller AM, Gopal AS, King DL. Left and right atrial volumes by free-hand three-dimensional echocardiography: in vivo validation using magnetic resonance imaging. Eur J Echocardiogr 2000;1:55–65.
10. Lang RM, Bierig M, Devereux RB, et al. Recommendations for chamber quantification: a report from the American Society of Echocardiography's Guidelines and Standards Committee and the Chamber Quantification Writing Group. J Am Soc Echocardiogr 2005;18:1440–63.
11. Quiñones MA, Otto CM, Stoddard M, Waggoner A, Zoghbi WA. Recommendations for quantification of Doppler echocardiography: a report from the Doppler Quantification Task Force of the Nomenclature and Standards Committee of the American Society of Echocardiography. J Am Soc Echocardiogr 2002;15:167–84.
12. Sallach JA, Tang WH, Borowski AG, et al. Right atrial volume index in chronic systolic heart failure and prognosis. J Am Coll Cardiol Img 2009;2:527–34.
13. DeLong ER, DeLong DM, Clarke-Pearson DL. Comparing the areas under two or more correlated receiver operator characteristic curves: a nonparametric approach. Biometrics 1988;44:837–45.
14. Maddukuri P, Viera MLC, DeCastro S, et al. What is the best approach for assessment of left atrial size? Comparison of various unidimensional and two-dimensional parameters with three-dimensional echocardiography determined left atrial volume. J Am Soc Echocardiogr 2006;19:1026–32.
15. Muller J, Burri J, Lerch R. Evaluation of right atrial size in patients with atrial arrhythmias: comparison of 2-dimensional versus real time 3-dimensional echocardiography. Echocardiography 2008;25:617–23.

16. Stein JH, Neumann A, Marcus R. Comparison of estimates of right atrial pressure by physical examination and echocardiography in patients with congestive heart failure and reasons for discrepancies. Am J Cardiol 1997;80:1615–8.
17. Delgado V, Vidal V, Sitges M, et al. Fate of left atrial function as determined by real-time three-dimensional echocardiography study after radiofrequency catheter ablation for the treatment of atrial fibrillation. Am J Cardiol 2008;101:1285–90.
18. Marsan NA, Tops LF, Holman ER, et al. Comparison of left atrial volumes and function by real-time three-dimensional echocardiography in patients having catheter ablation for atrial fibrillation with persistence of sinus rhythm versus recurrent atrial fibrillation three months later. Am J Cardiol 2008;102:847–53.

Key Words: cardiac volume ■ echocardiography ■ heart failure ■ imaging.