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Direct Measurement of Vena Contracta Area by Real-Time 3-Dimensional Echocardiography for Assessing Severity of Mitral Regurgitation

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Abstract

We tested the hypothesis that vena contracta (VC) cross-sectional area in patients with mitral regurgitation (MR) can be reproducibly measured by real-time three-dimensional echocardiography (RT3DE) and correlates well with volumetric effective regurgitant orifice area (EROA). Earlier MR repair requires accurate noninvasive measures, but VC area is practically difficult to image in 2D views, which are often oblique to it. 3DE can provide an otherwise unobtainable true cross-sectional view. In 45 patients with >mild MR, 44% eccentric, 2D and 3D VC areas were measured and correlated with EROA derived from regurgitant stroke volume. RT3DE VC area correlated and agreed well with EROA for both central and eccentric jets ($r^2=0.86$, $SEE=0.02\text{ cm}^2$, difference = $0.04\pm0.06\text{ cm}^2$, $p=NS$). For eccentric jets, 2DE overestimated VC width compared with 3DE ($p=0.024$) and correlated more poorly with EROA ($r^2=0.61$ vs. 0.85 , $p<0.001$), causing clinical misclassification in 45% of patients with eccentric MR. Interobserver variability for 3D VC area was 0.03 cm^2 (7.5% of the mean, $r=0.95$); intraobserver was 0.01 cm^2 (2.5%, $r=0.97$). In conclusion, RT3DE accurately and reproducibly quantifies vena contracta cross-sectional area in patients with both central and eccentric MR. Rapid acquisition and intuitive analysis promote practical clinical application of this central, directly visualized measure and its correlation with outcome.

Keywords

Mitral regurgitation; vena contracta; effective orifice area; 3D echocardiography

INTRODUCTION

Vena contracta (VC) area, one of the most direct assessments of mitral regurgitation (MR),^{1–3} is ideally measured in short axis perpendicular to the MR flow,^{4–16} but, as Hall et al⁷ noted, is generally difficult to identify in such a plane, as shown in Figure 1A: the narrowest neck of the jet is often impossible to include in any imaging plane available from transthoracic windows. Available planes cut obliquely across the flowstream and often include portions of

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the expanding jet, overestimating VC area. This problem is magnified when the jet is eccentric¹⁷ compared with central jets (Figure 1B). The recent advent of real-time 3-Dimensional echo (RT3DE) can potentially solve this problem.^{18–22} Once we have rapidly acquired the three-dimensional flowstream, a plane can be readily aligned with the VC even if unavailable from transthoracic windows (Figure 1C). We tested the hypothesis that RT3DE can provide such a measure of VC area in patients with both central and eccentric MR jets, and that this measurement correlates well with an independent volumetric measure of EROA derived from quantitative Doppler. We also correlated 3D-optimized versus standard 2D-imaged VC width (VCW) with EROA.

METHODS

We enrolled 49 consecutive patients with >mild MR by color Doppler.¹⁵ Patients were excluded for significant mitral stenosis (area <2.0 cm²), mitral prosthesis, irregular rhythm, or significant aortic insufficiency or stenosis (area <1.5 cm²). Studies were done with IRB approval for noninvasive imaging with verbal informed consent.

Patients were scanned in the left lateral decubitus position with a matrix-array transducer (Philips Sonos 7500, Andover, MA) using the narrowest sector possible to maximize frame rate. 3D acquisitions were obtained from a parasternal long-axis transducer orientation which aligned the central beam axis with the leaflet tips. The transducer was translated and rotated to maximize visualization of the proximal flow convergence region (PFCR), VC, and diverging jet within this plane. 3D data with Doppler color flow were automatically acquired over 7 beats by electrocardiographic gating with suspended respiration, Nyquist velocities of 40–68 cm/s, and maximal color gain that eliminated random noise.

Data sets were processed using Tomtec 4D Cardio-View™ software. The 3D image was automatically cropped medio-laterally direction to reveal the central imaging plane, which was translated and tilted to maximize the portions of the PFCR, VC, and jet visualized (Figure 2A). The frame showing the largest MR flow area was zoomed (early to mid-systolic for rheumatic or ischemic MR; mid- to late systolic for mitral valve prolapse).²³ The narrowest neck of the jet was identified and the PFCR cropped away (Figures 2B&C). The valve was then turned to view the VC en face (Figure 2D) and uncropped in the medio-lateral dimension to reveal the full VC cross-sectional area, which was planimetered, respecting surrounding leaflet borders.

Mitral inflow was measured as the time-velocity integral of pulsed-wave Doppler mitral annular modal velocities times mitral annular area as that of an ellipse with apical 4-chamber and 2-chamber diameters measured at maximal leaflet opening.^{7,24,25}

MR stroke volume was calculated as mitral inflow minus aortic outflow, calculated using pulsed Doppler at the aortic annulus times annular area (circular). EROA was calculated as MR stroke volume divided by the time-velocity integral of continuous-wave Doppler MR orifice velocities.⁵ EROA and VC areas were measured in a blinded manner.

The narrowest antero-posterior VC dimension was measured from the 3D image and independently from a zoomed 2D parasternal long-axis view imaged at 2.5 MHz, with the central beam through the leaflet tips and maximized visualization of the PFCR, VC, and proximal jet. VC width was defined as the narrowest width of the proximal jet measured at or in the immediate vicinity of the MR orifice at the leaflet tips,^{6,26} averaged over 3 cardiac cycles.

VC area by 3D echo was compared with EROA from quantitative Doppler (independent data) by linear regression and Bland-Altman analysis of agreement for the entire population and for central and eccentric jets. Eccentric jets adhered to the mitral leaflets and left atrial wall throughout their course. VC width by 2D and 3D methods were compared by paired t-test and

correlated with quantitative Doppler EROA by linear regression, with F-test to compare variances for central and eccentric jets.

As a check on the pulsed-wave Doppler measurements used to calculate EROA, we measured mitral inflow and aortic outflow in 10 additional patients with no aortic insufficiency and no-to-trace physiologic MR by color Doppler to insure they were not significantly different by paired t-test; (mitral inflow minus aortic inflow)/(mitral inflow) was calculated to obtain its standard deviation (range of calculated regurgitant fraction in the absence of important MR) and test the mean value versus 0.

Two independent observers repeated measurements of 3D-derived VC area and width, 2D VC width, and EROA in 10 patients. One observer repeated measurements one month later. Observer variability was assessed by linear regression and as standard deviation of observer differences as percent of pooled means.

RESULTS

Of the 49 patients enrolled, 4 were excluded for imaging limitations affecting the ability quantify VC or EROA, leaving 45 patients (28 men, 17 women, characteristics in Table 1).

VC area by 3D echo correlated well with quantitative Doppler EROA in the entire population (Figure 3A; $r^2=0.86$, $SEE=0.02\text{ cm}^2$) and in patients with both central and eccentric MR jets ($r^2=0.92$, $SEE=0.02\text{ cm}^2$; $r^2=0.86$, $SEE=0.02\text{ cm}^2$; Figures 3B&C). The differences between VC area and EROA were not significant ($0.04\pm0.06\text{ cm}^2$; Figure 3D).

VC width from 2D and 3D echo agreed well for central jets ($0.64\pm0.20\text{ cm}$ vs. $0.61\pm0.15\text{ cm}$), and both correlated well with quantitative Doppler EROA ($r^2=0.81$, 0.82 , Figure 4A). For eccentric jets, 2D VC width overestimated the minimal dimension by 3D echo ($0.65\pm0.13\text{ cm}$ vs. $0.54\pm0.16\text{ cm}$, $p=0.024$), with poorer correlation ($r^2=0.61$ vs. 0.85 , $p<0.001$; Figure 4B).

Based on published cutoffs, the 2D overestimation produced clinical misclassifications not resulting from the 3D approach: 5/5 patients with eccentric MR and EROA $<0.2\text{ cm}^2$ (mild MR) had 2D VC width $\geq 0.4\text{ cm}$ (moderate MR); 4/11 patients (36%) with EROA between 0.2 and 0.4 cm^2 (moderate) had 2D VC width $>0.7\text{ cm}$ (severe), for a total misclassification rate of 9/20 (45%).¹⁵

In 10 patients with no or trace MR, quantitative Doppler mitral inflow and aortic outflow were not significantly different (91.5 ± 8.3 vs $87.8\pm 9.9\text{ ml/beat}$, $p=0.11$). The calculated regurgitant fractions were $2\pm 6\%$, $p=\text{NS}$ vs. 0, indicating a reasonable range of variability.

Measurements of 3D VC area by 2 observers correlated well ($r=0.95$, standard deviation of differences= 0.03 cm^2 , or 7.5% of the mean). Intraobserver variability was 0.01 cm^2 (2.5%), $r=0.97$. Observer variability for quantitative Doppler EROA was 0.03 cm^2 for two observers (7.5%), $r=0.93$, and 0.02 cm^2 ($r=0.94$) for one. Observer agreement for 3D VC width was $r=0.92$, standard deviation= 0.02 cm for two observers and 0.01 cm ($r=0.95$) for intraobserver variability (6 and 3% of the mean). For 2D VC width, interobserver r was 0.95 , standard deviation= 0.06 cm .

DISCUSSION

The increasing trend to repair MR before LV functional deterioration demands accurate noninvasive MR quantification.¹⁵ The VC, the smallest area of flow beyond the orifice, is a central measure, reflecting the EROA, and requires standardized measurement.^{6,11} Two-dimensional images are limited in describing full VC area, which may vary in shape among

patients and at different sites across a valve. In practical experience, a true short-axis view of the VC is often difficult to obtain in standard 2D views,⁷ which often cut obliquely across the proximal jet due to either jet or cardiac angulation relative to the beam (Figs. 1A and C).

Real-time 3-Dimensional echo (RT3DE)^{18–22,27} can solve this problem, but practicality and accuracy must be established. Initial studies showed accuracy for VC in aortic insufficiency and ventricular septal defect by reconstructing rotated 2D views,^{28–30} but that approach is limited by the need to maintain a fixed transducer position during a prolonged acquisition. RT3DE has considerably accelerated and simplified image acquisition, while navigation tools now available onboard the scanner itself provide an intuitively reasonable and rapid method for standardizing flowstream dimensions. By viewing the jet from the side and cropping through its narrowest neck, we can obtain a cross-sectional view of the VC that may be unavailable from transthoracic windows. Although volumetric scanning with broad-beam formation may limit lateral resolution, the parasternal acquisition in this study allows most of the VC circumference to be imaged with the axial beam resolution, which should be preserved.⁹ The results show excellent correlation and agreement with an independent measure of EROA derived from regurgitant volume, and quantitatively confirm the tracking of values reported with semiquantitative angiographic grade.²⁷ The results are equally strong for eccentric jets, which are the most difficult to transect perpendicularly in 2D views,^{8,17} and there is clinically acceptable reproducibility.

Linear VC width was equivalent for central jets by both 2D and 3D techniques, since it is measured from a long-axis view. However, for eccentric jets, VC width by 2D echo was overestimated and correlated less well with EROA, producing frequent clinical misclassification. This may relate to a tendency to measure an apparent VC width delineated by the leaflet portions where the jet is seen to exit in 2D images, as opposed to the true narrowest neck, one border of which may lie somewhat proximal to the apparent leaflet exit in three dimensions for eccentric jets (Figure 1A). For an eccentric jet, overestimation may also relate to an oblique orientation of the 2D plane relative to the minor axis of the VC, which is then over-estimated relative to a true minor axis intersected by the more adjustable 3D cropping plane (Figure 5). Little et al.²² found that MR severity and orifice shape affected agreement of RT3DE VC area with PFCR-derived EROA, but also found a clear superiority of 3D in assessing eccentric jets, thereby strengthening the validity of our findings particularly relating to eccentric jets. This approach is an exciting one and a potential new standard for analyzing this important clinical problem.

One theoretical advantage of the 3D approach is that a 2D beam, if exactly perpendicular to the laminar VC flow, will measure a negligible Doppler velocity component. In the 3D approach, the beam need not be perpendicular to flow because the cross-sectional view is derived only by subsequent cropping. Concerns about limited lateral resolution at the lateral orifice are minimized by the counterbalancing effect of surrounding leaflet tissue that circumscribes the color area based on the tissue priority algorithm of ultrasound display. Although there is no ideal gold standard for comparison, quantitative Doppler uses completely independent data, and its correct application was verified in 10 patients without MR, showing no significant MR volume and low variability.^{7,24,25}

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Figure 1**A**

Figure 1**B**

Figure 1**c** **Figure 1.**

A, Eccentric jet: Schematic indicating how a view from a standard parasternal transducer position sections the proximal MR jet oblique to its narrowest neck or vena contracta (VC), and overestimates VC cross-sectional area. A true cross-sectional plane (arrows) is unavailable from transthoracic 2D windows, but can be positioned through the jet after 3D acquisition. Ao=aorta, LA=left atrium, LV=left ventricle, RV=right ventricle. **B, Central jet:** This obliquity is avoided for central jets when the LV long axis parallels the chest wall. **C, Central jet:** Oblique cardiac orientation relative to the chest wall also positions transthoracic 2D echo views oblique to the VC.

Figure 2.

A: The 3D cardiac image is automatically cropped in a medio-lateral direction to reveal the central imaging plane; this plane is translated and tilted to maximize portions of the proximal flow convergence region, vena contracta, and diverging jet visualized in it. **B,C:** The narrowest neck of the jet is identified and the more proximal flow region cropped away. **D:** The valve is then turned to view the vena contracta en face and planimeter its area.

Figure 3 **Figure 3**

Figure 3**D** **Figure 3.**

Linear regression analysis of 3D VC area vs quantitative Doppler effective regurgitant orifice area (EROA) for the total MR population (**A**) and those with central and eccentric jets (**B** & **C**). **D**: Bland-Altman analysis of differences between 3D VC area by direct tracing and EROA by quantitative Doppler.

Figure 4.

Linear regression analysis of 2D and 3D VC width vs volumetric EROA for central (A) and eccentric (B) MR jets, showing clinically important overestimation by 2D for eccentric jets.

Figure 5. 2D VC width may also be oblique to the true VC minor dimension for an eccentrically originating jet (**B**); 3D echo allows alignment of the measured VC width with the true minor dimension. This is not a limitation for central jets (**A**).

Table 1

Patient characteristics for the total study population and those with central and eccentric MR jets. VC=vena contracta, MR=mitral regurgitation, MV=mitral valve, AV=aortic valve, SV=stroke volume, EF=ejection fraction, RV=regurgitant volume, RF=regurgitant fraction, FMR=Functional MR(Ischemic Heart Disease), MVP=Mitral valve prolapse, RHD=Rheumatic Heart Disease.

Variables	Total (n=45)	Central (n=25)	Eccentric (n=20)	P- Value
Age	64.2±4.5	62.9±6.4	65.1±4.1	NS
Male/Female	28/17	16/10	12/7	NS
Mitral Valve-inflow SV(ml)	121.7±25.3	112.1±19.4	131.4±27.2	NS
Aortic Valve-outflow SV(ml)	60.0±14.8	57.7±14.1	62.3±15.4	NS
Ejection Fraction	36.0±10.8	34.3±10.6	38.3±8.2	NS
Regurgitan Volume by Doppler (ml)	61.71±19.18	54.41±17.81	69.02±18.04	<i>a, b, c</i>
Mitral Regurgitation Regurgitant Fraction	40.58±10.10	40.03±12.39	41.14±7.42	NS
Ischemic Heart Disease	26 (58%)	15	11	
Mitral Valve Prolapse	10 (22%)	3	7	
Rheumatic Heart Disease	9 (20%)	3	6	

^aP<0.05 for total vs central,

^bP<0.05 for total vs eccentric,

^cP<0.05 for eccentric vs central.