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Assessment of Aortic Regurgitation by Transesophageal Color Doppler Imaging of the Vena Contracta: Validation Against an Intraoperative Aortic Flow Probe

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OBJECTIVES This study was performed to validate the accuracy of color flow vena contracta (VC) measurements of aortic regurgitation (AR) severity by comparing them to simultaneous intraoperative flow probe measurements of regurgitant fraction (RgF) and regurgitant volume (RgV).

BACKGROUND Color Doppler imaging of the vena contracta has emerged as a simple and reliable measure of the severity of valvular regurgitation. This study evaluated the accuracy of VC imaging of AR by transesophageal echocardiography (TEE).

METHODS A transit-time flow probe was placed on the ascending aorta during cardiac surgery in 24 patients with AR. The flow probe was used to measure RgF and RgV simultaneously during VC imaging by TEE. Flow probe and VC imaging were interpreted separately and in blinded fashion.

RESULTS A good correlation was found between VC width and RgF ($r = 0.85$) and RgV ($r = 0.79$). All six patients with VC width >6 mm had a RgF >0.50. All 18 patients with VC width <5 mm had a RgF <0.50. Vena contracta area also correlated well with both RgF ($r = 0.81$) and RgV ($r = 0.84$). All six patients with VC area >7.5 mm^2 had a RgF >0.50, and all 18 patients with a VC area <7.5 mm^2 had a RgF <0.50. In a subset of nine patients who underwent afterload manipulation to increase diastolic blood pressure, RgV increased significantly (34 ± 26 ml to 41 ± 27 ml, $p = 0.042$) while VC width remained unchanged (5.4 ± 2.8 mm to 5.4 ± 2.8 mm, $p = 0.41$).

CONCLUSIONS Vena contracta imaging by TEE color flow mapping is an accurate marker of AR severity. Vena contracta width and VC area correlate well with RgF and RgV obtained by intraoperative flow probe. Vena contracta width appears to be less afterload-dependent than RgV. (J Am Coll Cardiol 2001;37:1450–5) © 2001 by the American College of Cardiology

Doppler color flow mapping is widely used to assess the severity of valvular regurgitation because it is convenient, noninvasive and offers real-time visualization of the regurgitant jet. Unfortunately, visual grading of the severity of valvular regurgitation by this technique is inaccurate because various hydrodynamic variables and instrument settings affect color flow jet display (1–3). Therefore, vena contracta (VC) imaging has emerged as an alternative to visual grading that is simpler to use than quantitative techniques (4–11). The VC is the narrowest portion of a jet located at or just distal to its orifice (12,13). It is slightly smaller than the anatomic orifice due to contraction of the flow stream by viscous friction and boundary layer effects (12). However, its cross-sectional area is equivalent to the effective regurgitant orifice area, an important measure of lesion severity in valvular regurgitation (14–16).

Vena contracta imaging has been well studied in mitral regurgitation (4–9), with fewer data for aortic regurgitation (AR). In 1987, Perry et al. (17) showed that the height of the AR jet by color flow mapping indexed by the diameter of the left ventricular outflow tract correlated with angiographic grading. Although this index is semiquantitative, it became the clinical standard for echocardiographic grading of AR. In animal models of AR, the VC correlates well with regurgitant volume (RgV) and orifice area measured by flow probes on the aorta and pulmonary artery (18–21). Recently, Tribouilloy et al. (11) demonstrated that VC imaging of AR predicts quantitative Doppler estimates of RgV and orifice area. To our knowledge, VC imaging of AR jets by transesophageal echocardiography (TEE) has not been reported, despite the fact that TEE is often necessary to evaluate AR in patients with technically difficult transthoracic studies or in the intensive care unit or operating room. This study was done to compare VC imaging of AR by TEE to simultaneously determined regurgitant fraction (RgF) measured by a flow probe on the aorta during open heart surgery.

METHODS

Patient population. The protocol was approved by the Institutional Review Boards at the University of Texas Southwestern Medical Center, Parkland Memorial Hospital and the Dallas VA Medical Center. All patients gave written informed consent. The consent form specified that

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Abbreviations and Acronyms

AR = aortic regurgitation
CABG = coronary artery bypass grafting
RgF = regurgitant fraction
RgV = regurgitant volume
TEE = transesophageal echocardiography
VC = vena contracta

the protocol would prolong their operation by about 15 min and that there was an increased risk of infection or bleeding due to flow probe placement. We studied patients undergoing cardiac surgery (aortic valve surgery or coronary artery bypass grafting [CABG]) at Parkland Memorial Hospital or the Dallas VA Medical Center who had preoperative evidence of AR by echocardiography. In addition, eight patients undergoing CABG without AR were studied as control subjects. Patients were excluded from participation if the aortic root diameter was too large for the aortic flow probe, if they had more than mild mitral regurgitation or if the surgeon considered the placement of the flow probe to increase operative risk.

A total of 24 patients completed the study. There were 22 men and 2 women ranging in age from 23 to 79 (mean 56 ± 15) years. The causes of AR were aortic atherosclerosis ($n = 7$), endocarditis ($n = 5$), dilated aortic root ($n = 3$), bicuspid valve ($n = 1$), rheumatic fever ($n = 1$), a flail leaflet ($n = 1$) and uncertain ($n = 6$). Aortic valve replacement was performed in 13 patients; 11 patients with mild AR were studied during CABG surgery.

Experimental design. Following median sternotomy, but prior to initiation of cardiopulmonary bypass, a transit time flow probe was placed on the ascending aorta. Simultaneous assessment of AR was made by TEE using color flow mapping of the VC and by intraoperative aortic flow probe. In a subset of nine patients, blood pressure was increased with phenylephrine, and flow probe and TEE measurements were repeated. Phenylephrine was not given to patients with hypertension, severe left ventricular dysfunction or unstable coronary artery disease.

TEE. After induction of general anesthesia, a 5-MHz multiplane probe (Agilent Technologies, Andover, Massachusetts or Vingmed GE Medical Systems, Horten, Norway) was inserted. For each patient, color flow gain was adjusted downward to the point at which background noise just disappeared; the gain setting was maintained at that level. To maximize the frame rate and line density, the narrowest possible sector angle that enabled visualization of the VC was used. The imaging depth was set as low as possible to maximize the size of the aortic valve and left ventricular outflow tract. The Nyquist velocity was maintained at the maximum value for that imaging depth. It was not adjusted downward, nor was baseline shift performed.

Long-axis and short-axis images of the aortic valve were obtained from the mid-to-upper esophagus. In the long-axis view, color flow imaging was performed with adjustment of the imaging plane to optimize visualization of the VC of the AR jet (Fig. 1, left). The largest diameter of the VC during any portion of diastole was measured. For eccentric jets, the VC width was always measured perpendicular to the long-axis of the jet. In addition, the diameter of the aortic annulus was measured at the base of the leaflets. The scan plane was then rotated to a short-axis view of the VC at the aortic valve level. The probe depth and tip flexion were adjusted to display the smallest area of the AR jet as it passed through the regurgitant orifice (Fig. 1, right). The cross-sectional area of the VC was obtained by planimetry.

All TEE images were recorded on videotape and were analyzed separately by two experienced observers blinded to the aortic flow probe and clinical data. The width and cross-sectional area of the VC were measured for three to five beats and the results averaged.

Aortic flow probe data. Flow probes specifically manufactured for measuring human aortic blood flow intraoperatively were used (Transonics, Ithaca, New York). Three sizes were utilized: 28 mm, 32 mm and 36 mm. These probes employ an X-shaped array of four ultrasound transducers that determine flow by the transit-time technique (22,23). This design fully illuminates the aortic flow field, which is critical since major changes in flow profile occur

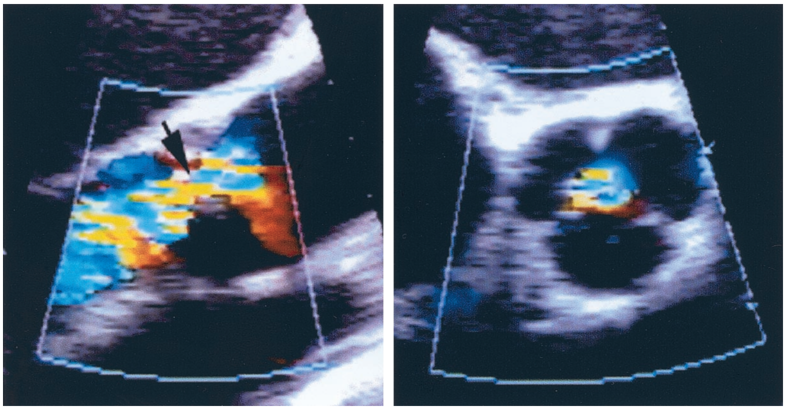

Figure 1. Representative images of the vena contracta from a patient in this study. **Left**: the long-axis view; **right**: the short-axis view.

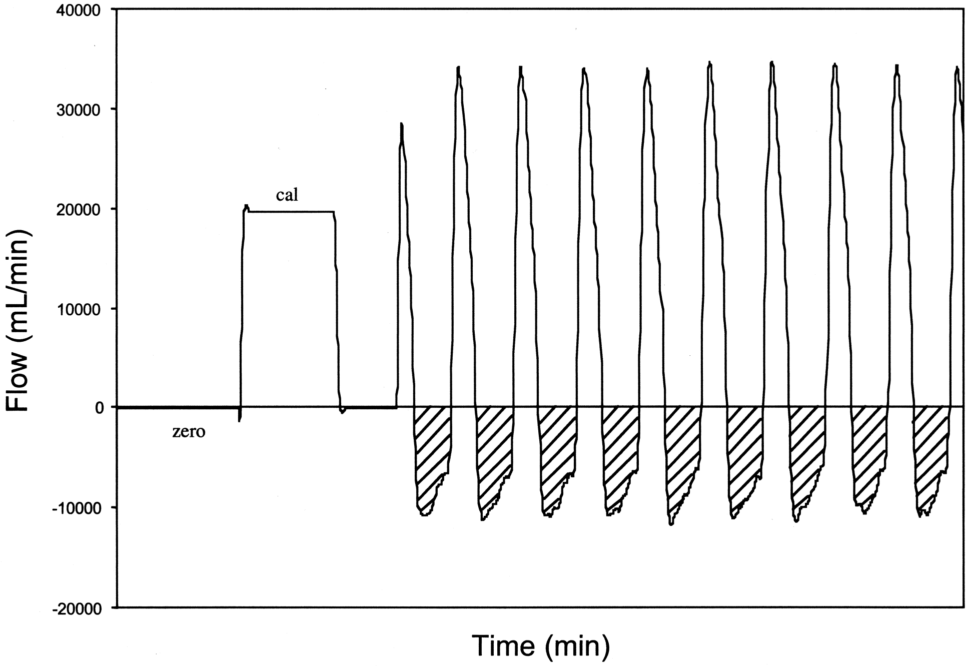

Figure 2. Representative flow probe tracing from a patient in this study. Electronic zero and calibration (cal) are shown toward the left. The flow signal above the baseline displays forward flow in the ascending aorta; regurgitant flow is below the baseline **(striped area)**.

across the ascending aorta during the cardiac cycle. Accordingly, these probes have a relative accuracy of ±2% and a resolution of 0.04 to 0.08 liter/min for bidirectional aortic flow (22,23). Following median sternotomy, the ascending aorta was isolated and sized. The appropriately sized flow probe was positioned on the ascending aorta with warm, sterile saline solution used as an acoustic couplant. The flow probe was interfaced to a HT107 flowmeter (Transonics, Ithaca, New York) with a digital port to download the flow signal into a laptop computer. This digital signal was electronically zeroed and calibrated. The digital flow probe data were stored in a spreadsheet (Excel, Microsoft, Redmond, Washington). Integration of the forward flow signal over five consecutive beats was used to determine forward stroke volume. Integration of the retrograde flow signal over five consecutive beats was used to determine RgV. Figure 2 shows a representative flow probe signal from a patient in this study.

Statistical methods. Linear regression analysis was used to compare baseline measurements of VC width and cross-sectional area to RgV and RgF. In the subset of patients in whom an increase in blood pressure was achieved by administration of phenylephrine, a paired *t* test was used to assess the effect of a change in afterload on RgV and VC width. Interobserver variability was assessed by linear regression with Bland-Altman analysis. A p value of <0.05 was considered statistically significant.

RESULTS

Control subjects. In the eight subjects without AR, there was either complete absence of (n = 4) or a very small diastolic negative deflection on the flow probe tracing representing coronary flow (n = 4). This false RgV averaged <2 ml and was considered negligible. Thus, the negative deflection in patients with AR was not corrected for coronary backflow.

Comparison of VC width and AR severity. Vena contracta width in the long-axis view correlated well with aortic RgF by intraoperative aortic flow probe ($r^2 = 0.72$) (Fig. 3, left). All six patients with a VC width >6 mm had a RgF of >0.50; all 18 patients with a VC width <5 mm had a RgF of <0.50. Vena contracta width also correlated with aortic RgV by aortic flow probe, but less strongly ($r^2 = 0.63$; Fig. 3, right). A VC width <6 mm predicted a RgV <40 ml in 17 of 18 patients (94%). A VC width >6 mm predicted a RgV >40 ml in 4 of 6 patients (67%). Two patients (closed circles in Fig. 3, right) with acute severe AR had VC widths >6 mm and RgFs >0.50, but RgVs <40 ml. Both patients had acute AR—one due to endocarditis and the other due a flail aortic valve leaflet after chest trauma. Indexing the VC width for aortic annulus diameter did not improve the correlation with RgF or RgV.

Comparison of VC area with AR severity. Vena contracta area in the short-axis view correlated with aortic RgF ($r^2 = 0.65$) (Fig. 4, left) and aortic RgV ($r^2 = 0.71$) (Fig. 4, right). All six patients with a VC area >7.5 mm^2 had a RgF of >0.50; all 18 patients with a VC width <7.5 mm^2 had a RgF of <0.50. A VC area >7.5 mm^2 predicted a RgV >40 ml in 4 of 6 patients (67%); whereas a VC area <7.5 mm^2 predicted a RgV <40 ml in 17 of 18 patients (94%). The two patients with acute severe AR had VC areas >7.5 mm^2 but RgVs <40 ml.

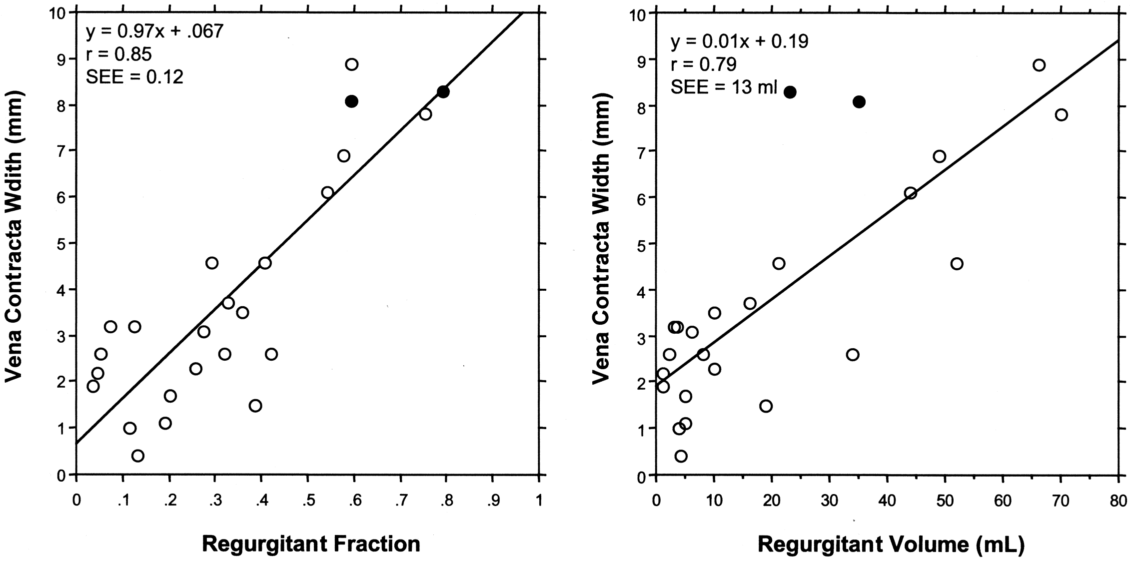

Figure 3. Linear regression plots showing a comparison of vena contracta width in the long-axis view to regurgitant fraction **(left)** and regurgitant volume **(right)**. The two patients depicted by **dark circles** had acute severe aortic regurgitation.

Interobserver variability. Interobserver agreement for VC width was good ($r = 0.94$, $p < 0.0001$) with a standard error of the estimate of 0.96 mm. Similarly, agreement was good for VC area ($r = 0.95$, $p < 0.0001$) with a standard error of the estimate of 0.28 mm^2.

Afterload dependence of VC width and RgV. In a subset of nine patients, blood pressure was significantly increased by either intravenous phenylephrine ($n = 8$) or volume infusion ($n = 1$) and repeat measurements of VC width by TEE and AR severity by aortic flow probe were made. Table 1 shows the hemodynamic changes observed. A statistically significant increase in RgV by aortic flow probe was found (34 ± 26 ml to 41 ± 27 ml, $p = 0.04$). Vena contracta width by TEE did not change (5.4 ± 2.8 mm to 5.4 ± 2.8 mm, $p = 0.41$).

DISCUSSION

This study demonstrates that VC imaging of AR jets by TEE correlates well with direct measurements of RgF and RgV by aortic flow probe. A particular strength of this study is the simultaneous acquisition of TEE and flow probe data. Moreover, the transit time flow probes used in this study are more accurate than electromagnetic flow probes and, therefore, provide a high quality reference standard for blood flow measurement in the aorta (22,23).

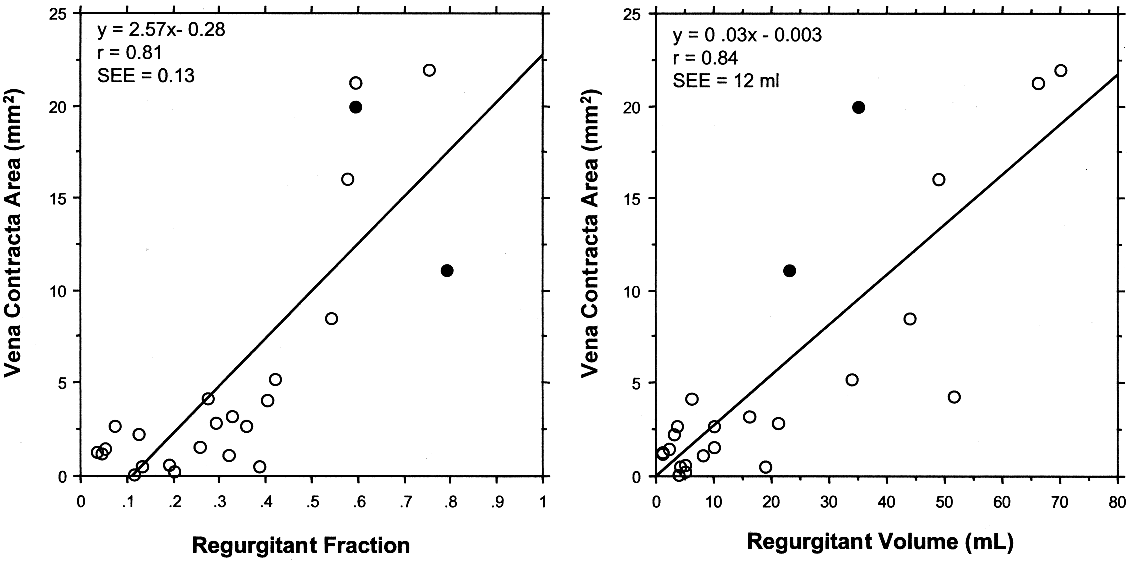

Figure 4. Linear regression plots showing a comparison of vena contracta area in the short-axis view to regurgitant fraction **(left)** and regurgitant volume **(right)**. The two patients depicted by **dark circles** had acute severe aortic regurgitation.

Table 1. Hemodynamic Changes After Intraoperative Manipulation of Afterload

Characteristic	Baseline	Increased Afterload	p Value
Systolic blood pressure (mm Hg)	106 ± 12	124 ± 26	0.009
Diastolic blood pressure (mm Hg)	46 ± 14	51 ± 10	0.034
Heart rate (beats/min)	75 ± 10	64 ± 14	0.008
Regurgitant volume (ml)	34 ± 26	41 ± 27	0.042
Regurgitant fraction	0.44 ± 0.23	0.50 ± 0.20	0.090
Vena contracta width (mm)	5.4 ± 2.8	5.4 ± 2.8	0.41

Comparison to previous studies. Ishii et al. (18,19) published two studies comparing VC width by epicardial echocardiography to RgF and RgV obtained by flow probes in sheep with chronic AR. They found that VC width was superior to jet length or jet area and was accurate in the setting of eccentric jets. The correlation coefficients observed in our clinical study of intraoperative TEE are very similar to those found in the sheep model. Tribouilloy et al. (11) recently published a comparison of VC width by transthoracic echocardiography to quantitative Doppler measures of RgF, RgV and effective regurgitant orifice area in 79 patients. They found good correlations between VC width and all three measures of AR severity. They did not measure VC area. The results of the present study of VC width by TEE are remarkably similar to those of Tribouilloy et al. (11) in terms of the correlation coefficients and the cutoff values for diagnostic accuracy. For example, a VC width >6 mm by TEE strongly predicts severe AR and a VC width <5 mm strongly predicts nonsevere AR, cutoff values that are identical to those found in the study of Tribouilloy et al. (11) of transthoracic imaging.

We also measured VC cross-sectional area in the short-axis view and found that it correlated well with flow probe measures of RgF and RgV. Lateral resolution was maximized by using the smallest sector angle that allowed visualization of the aortic valve. Vena contracta area correlated well with RgF and RgV with a cutoff value of 7.5 mm^2 appearing to provide the best separation of severe from nonsevere AR. There were two patients in whom acute severe AR resulted in high RgFs but only moderately elevated RgVs. Both presented with congestive heart failure and were small individuals with small left ventricular volumes. This highlights the fact that RgV is not always the best indicator of AR severity. In these patients, VC width was a better index of AR severity than RgV, supporting the concept that effective regurgitant orifice area is an important marker of lesion severity (14–16).

Load dependence of the VC in AR. In vitro studies using a fixed orifice demonstrate that the VC is independent of flow rate (12,13) and, therefore, should be less influenced by loading conditions than traditional indexes of AR severity such as RgV or RgF. However, in the clinical setting, the regurgitant orifice is often dynamic rather than fixed (24,25). In mitral regurgitation, the VC width has been shown to increase, decrease or remain the same with acute afterload reduction, depending on orifice geometry and etiology (26). In the present study, a subset of nine patients underwent afterload manipulation in which a small increase in RgV was seen without a change in VC contracta width. This supports the concept proposed by others that the effective regurgitant orifice area is not as load dependent as RgV in AR (25,27). This probably applies predominantly to degenerative atherosclerotic AR (even superimposed on a bicuspid valve) because such valves typically have a relatively fixed orifice. However, in the setting of AR secondary to a dilated aortic root, the regurgitant orifice, and hence the VC, may be dynamic and may change with different loading conditions (25,27). The fact that RgV changed only a small amount with afterload increase is consistent with the Gorlin hydraulic orifice equation in which the effect of a change in driving pressure on RgV is mitigated by its square root, as eloquently explained by Levine and Gaasch (25).

Study limitations. Since the VC is identical to the effective regurgitant orifice area, it would have been optimal to compare these two parameters. It is expected that VC measurements would have correlated even better to effective regurgitant orifice area than to RgF and RgV. To do so would have required dividing the RgV obtained by the flow probe by the velocity-time integral of the AR jet by continuous-wave Doppler. Although the latter can be done in most patients by TEE from a deep transgastric view, the limited time available during this intraoperative study prevented us from doing so. Nevertheless, the good correlation of VC width to the flow probe data and the lack of change in VC width during blood pressure increase validates the use of VC imaging by the TEE approach.

The sample size in this study is relatively small. However, the complex nature of a study involving simultaneous VC imaging during intraoperative flow probe placement makes it difficult to enroll large numbers of patients.

We were careful to manipulate the imaging plane to optimally align with the VC. However, VC width is a unidimensional measurement and may not truly reflect the severity of the lesion if the regurgitant orifice is elliptical or complex in shape (28,29). The addition of short-axis VC area is helpful in identifying such patients but may overestimate effective regurgitant orifice area if the imaging plane is below the valve such that it transects the expanding portion of the jet or if it is tangentially aligned. These problems will likely be overcome in the future by three-dimensional imaging of the VC (21).

CONCLUSIONS

Vena contracta imaging by TEE color flow mapping is an accurate marker of the severity of AR. It correlates well with RgF obtained by intraoperative flow probes and appears to be less dependent on loading conditions than RgV.

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