Application of Color Doppler Flow Mapping to Calculate Effective Regurgitant Orifice Area
An In Vitro Study and Initial Clinical Observations

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Background. Analogous to stenotic valve area in the assessment of valvular stenosis, regurgitant orifice area (ROA) represents a fundamental parameter to assess valvular insufficiency. However, this parameter has not been routinely available up to now. In this study, we introduce the concept and provide the methodology to calculate regurgitant orifice area noninvasively, based on the analysis of the proximal flow convergence zone.

Methods and Results. In an in vitro study, we showed the feasibility and the accuracy of calculating effective ROA by the proximal flow convergence method throughout a range of driving pressures. The calculated and true ROAs showed an excellent correlation with $r=.992$, $\Delta$ROA $= -1.4 \pm 2.9$ mm$^2$. We then applied this concept clinically in 77 patients with mitral regurgitation and showed a very good correlation between effective ROA calculated by the proximal flow convergence method and calculated by the Doppler echocardiographic method: $r=.95$, $\Delta$ROA $= -0.2 \pm 3.9$ mm$^2$. The ROA also correlated very well with Doppler echocardiographic-derived regurgitant stroke volume ($r=.93$) and regurgitant fraction ($r=.82$). In a subgroup of 20 patients who underwent invasive evaluation, the calculated effective ROA also correlated well with the angiographic grade of mitral regurgitation ($r=.81$).

Conclusions. We conclude that effective ROA represents unique information on the severity of a regurgitant lesion and can easily be calculated by the proximal flow convergence method. This new parameter should enhance our understanding and improve the serial assessment of valvular regurgitation. (Circulation. 1993;88:1150-1156.)

Key Words • echocardiography • Doppler • valvular regurgitation

A more detailed assessment of valvular incompetence remains an important goal in clinical cardiology. Currently, regurgitant lesions are predominantly being assessed in a semiquantitative manner, based on the extent and intensity of contrast in the receiving chamber by ventriculography or aortography$^{1,2}$ or on simple measurements of height, length, or area of the regurgitant jet by color Doppler flow mapping.$^{3-5}$ In the case of mitral regurgitation, quantitative left ventriculography has the potential to calculate regurgitant stroke volume and regurgitant fraction; however, this technique has several limitations and is not routinely performed in clinical practice.$^{6-8}$

Recently, two new quantitative approaches have been proposed to assess valvular regurgitation noninvasively using color Doppler echocardiography: the momentum technique$^{9,10}$ and the proximal flow convergence method.$^{11,12}$ Both techniques allow calculation of instantaneous or peak flow rate, regurgitant stroke volume, and regurgitant flow rate. In general, both semiquantitative and quantitative assessments of valvular regurgitation have focused on an estimation of the regurgitant volume. However, it must be realized that the regurgitant volume is determined not only by the severity of the valvular lesion itself but is also significantly affected by changes in hemodynamic conditions.

Recently, calculation of aortic regurgitant orifice area (ROA) was proposed as a new parameter to assess severity of aortic regurgitation.$^{13}$ However, this approach involved the placement of a Doppler catheter in the aortic root and therefore will not be routinely available for serial follow-up. In this study, we introduce the concept of effective ROA as a more fundamental parameter to assess the severity of valvular lesions and provide the methodology to calculate effective ROA noninvasively. Analogous to the calculation of a stenotic valve area in mitral or aortic stenosis, the ROA represents unique information on valvular regurgitant lesions that has not been routinely available up to now. The proximal flow convergence method appears to be a promising approach to quantify valvular regurgitation and has been validated numerically, experimentally, and...
clinically.\textsuperscript{11,14,15} This method allows one to calculate not only regurgitant stroke volume and regurgitant flow rate but also provides the information to calculate regurgitant orifice area.

The aim of this study was to investigate in an in vitro model the feasibility and the accuracy of calculating effective orifice area based on the analysis of the converging flow field proximal to a regurgitant orifice. We then applied this theoretical concept in the clinical setting to assess in vivo the size and range of regurgitant orifice areas present in a group of 77 patients with mitral regurgitation described previously in part.\textsuperscript{15} The effective regurgitant orifice areas calculated by this method were compared with the regurgitant orifice areas obtained by the Doppler echocardiographic method. Effective regurgitant orifice area was also compared with regurgitant stroke volume and regurgitant fraction obtained by pulsed Doppler subtraction of aortic and mitral flows in all patients and with angiographic grade of mitral regurgitation in a subgroup of 20 patients.

Methods

Theoretical Background

Recently, the proximal flow convergence method has been proposed as a promising approach to assess valvular regurgitation. Hydrodynamic theory predicts that flow converges toward a restrictive orifice as a series of isovelocity shells with decreasing surface area and increasing velocity. For a circular orifice with planar surroundings, these shells are roughly hemispheric except in the immediate vicinity of the orifice. By the principle of conservation of mass, flow rate \( Q \) can be calculated at any of the converging shells as the product of the isovelocity surface area times the velocity at that shell. At the level of the orifice, flow rate \( Q \) is simply calculated as the product of effective regurgitant orifice area (ROA) times orifice velocity \( v_o \): \( Q = \text{ROA} \times v_o \). (1). Assuming hemispheric symmetry of the proximal flow field, orifice flow rate \( Q \) can also be calculated as \( Q = 2 \pi r^2 \times v \). (2), where \( v \) is the velocity at a distance \( r \) from the orifice. By rearranging Equations 1 and 2, the effective regurgitant orifice area (ROA) can easily be obtained by

\[
\text{ROA} = \frac{2 \pi r^2 v}{v_o} = \frac{Q}{v_o}
\]

Velocity \( v \) and distance \( r \) can be read out from the color Doppler flow map either on screen or digitally. Orifice velocity \( v_o \) is obtained by continuous-wave Doppler.

In Vitro Experiment

A previously described in vitro model was used for this study.\textsuperscript{10} Briefly, this Plexiglas model produces steady flow between two chambers divided by a septum with a mount for different orifices. Flow enters the proximal chamber by gravity orifice from an upper reservoir and is forced into the distal chamber via a circular orifice with cross-sectional areas ranging from 0.1 to 1.0 cm\(^2\). The fluid (1% to 2% aqueous suspension of cornstarch to provide acoustic reflectors) leaves the distal chamber via an overflow outlet, which maintains a steady pressure difference between both chambers. The peak velocity (measured by continuous-wave Doppler) was varied from 190 cm/s to 510 cm/s with flow rates ranging from 23.3 cm\(^3\)/s to 245 cm\(^3\)/s, measured by timed collections. To investigate the effect of driving pressure on the accuracy of the regurgitant orifice area calculations based on the proximal flow convergence method, a range of different hydrodynamic stages was tested for each orifice size.

Echocardiographic data. Color Doppler flow images of the converging flow field were obtained using a research prototype Ultramark 9 (Advanced Technology Laboratories, Bothell, Wash), equipped with a digital dataport. A 2.25-MHz phased-array transducer was used with the largest packet size (number of pulses averaged per color scan line) and the lowest wall filter available (50 Hz). The color gain was adjusted to avoid artifactual color noise. All images were obtained at a pulse repetition frequency of 1250 Hz with a corresponding Nyquist velocity of 21 cm/s. For each stage, eight representative color-flow images were digitally stored.

Data analysis. For each stage, eight digitally output Doppler velocity maps were averaged. Subsequently, flow rate calculations were performed using an automated algorithm previously described and validated in this in vitro model.\textsuperscript{16} The algorithm first defines the location of the orifice by correlating an assumed velocity distribution where \( v = \cos \phi r \) (\( \phi \) is the angle between the direction of the flow and the ultrasound beam, \( r \) is the distance to the presumed orifice) with the observed velocities in the digital map. The tested orifice location with the highest correlation coefficient between predicted and observed velocity field is used for subsequent flow rate calculations.

It must be noted, however, that the entire velocity field is not used but only that region where the velocities are reliably displayed by color Doppler. As shown in Fig 1, there are several regions that must be excluded for analysis. First, in the immediate vicinity of the orifice, velocities rise above the Nyquist limit and are therefore not uniquely displayed. Also close to the orifice, the isovelocity contours flatten out and the hemispheric assumption does not hold. Second, at significant distance from the orifice, velocity is very low, and small
fluctuations in the flow field and the coarse velocity quantization of color Doppler flow mapping (typically 5-bit or 32-bin resolution) can introduce significant errors. Finally, regions more than 45° off of the central axis have such a high value for φ that the signal-to-noise ratio within the flow field becomes unacceptable.

Calculations. Once the orifice location was determined, flow rate (Qc) is automatically calculated as $Q_c = 2\pi r^2 v_0$, where $v_0$ is the observed velocity at a distance $r$ from the defined orifice location. The effective regurgitant orifice area (ROAe) was subsequently calculated as the orifice flow rate (Qc), calculated by the proximal flow convergence method, divided by the orifice velocity ($v_o$), measured by continuous-wave Doppler: $ROA_e = Q_c / v_0 = 2\pi r^2 v_0 / v_0$. The true effective ROA was obtained by dividing true flow rate (Q), measured by timed collections, by the orifice velocity ($v_o$).

Clinical Study

In a group of 77 patients with mitral regurgitation, we calculated effective ROA based on the analysis of the proximal flow convergence zone; this was compared with the ROA obtained by the Doppler echocardiographic method. This calculated effective ROA was also compared with quantitative indices of regurgitation: regurgitant stroke volume and regurgitant fraction, obtained by the Doppler echocardiographic method. In 20 patients undergoing cardiac catheterization, angiographic grading of mitral regurgitation was performed.

Echocardiographic examination. All M-mode, two-dimensional, Doppler, and color Doppler data were obtained as part of the routine echocardiographic evaluation. Commercially available echocardiographs (Hewlett-Packard 77020A and Sonos 1000, Andover, Mass) equipped with a 2.5-MHz transducer were used, and all images and spectral flow profiles were recorded on half-inch tape for off-line analysis. The clinically used echocardiographs were not equipped with digital storage and retrieval capabilities. Color Doppler images for analysis of the proximal flow convergence were obtained from an apical scanning window with typical Nyquist velocities of 49 to 58 cm/s. The narrowest color sector angle (30°) was used to maximize the color-flow imaging frame rate (15 to 17 Hz). The ventricular side of the mitral leaflets was carefully scanned for the presence of a region of flow convergence proximal to the regurgitant lesion (Fig 2). To optimize the visualization of the proximal flow convergence, the color baseline was shifted downward in the direction of the flow to highlight larger isovelocity contours with lower associated aliasing velocities. Since these larger isovelocity contours are at a further distance from the orifice, their larger associated radii are easier to measure. One also avoids the region close to the orifice where progressive flattening of the isovelocity contours occurs and the

FIG 2. An example of a proximal flow convergence zone at the ventricular side of the mitral leaflets in a patient with mitral regurgitation. The color baseline is shifted downward (white arrow) to highlight a lower isovelocity contour at a distance from the orifice with a corresponding velocity of 29 cm/s (small white arrows). LV indicates left ventricle; MV, mitral valve; and LA, left atrium.
assumption of simple hemispheric symmetry of the flow field leads to systematic underestimation of flow rate.

**Cardiac catheterization and angiography.** Right- and left-sided cardiac catheterization and left ventriculography were performed by standard techniques. Left ventriculography was performed in a single-plane 30° right anterior oblique projection in five patients and biplane 30° right and 60° left anterior oblique projections in 15 patients. Mitral regurgitation was graded according to standard criteria: grade I, mild; grade II, moderate; and grade III, severe. All angiograms were evaluated by a cardiac radiologist who was blinded to the echocardiographic and Doppler findings. For the majority of patients undergoing an invasive study, the Doppler echocardiographic data were acquired in the catheterization laboratory just before cardiac catheterization. In all patients, the echocardiographic study was performed within 24 hours of the invasive procedure.

**Calculations.** All M-mode and spectral tracings, twodimensional, and color Doppler flow images were analyzed off line using a computer analysis system (Sony SUM 1010). For the clinical application of the proximal flow convergence method, the frame with the largest proximal flow convergence region in midystole from at least five cardiac cycles was determined and assumed to coincide with the moment of peak regurgitant flow rate. Only the frames where the edges of the isovelocity contour of interest were uniform and well defined were considered for analysis. Peak instantaneous flow rate \( (Q_p) \) was calculated as \( Q_p = 2\pi r^2 v_\phi \), where \( r \) is the radius of the isovelocity contour of interest and \( v_\phi \) is the corresponding aliasing velocity, read out from the color calibration bar. The radius of the isovelocity surface was measured from the blue-to-red aliasing contour to the regurgitant orifice. However, the location of the regurgitant orifice often could not be defined. In that case, the radius was measured up to the level of the mitral leaflets. The effective regurgitant orifice area \( (ROAp) \) was then calculated as the peak flow rate \( (Q_p) \) divided by the peak regurgitant orifice velocity \( (v_\phi) \), measured by continuous-wave Doppler: \( ROAp = Q_p / v_\phi \). Multiplying \( ROAp \) by the mitral regurgitant time-velocity integral yields the regurgitant stroke volume.

Our overall approach to the Doppler echocardiographic quantification of mitral regurgitation has been described recently.\(^{15,20}\) Mitral forward stroke volume is obtained by the method of Fisher et al\(^\text{17}\) as the product of mean diastolic mitral orifice area and mitral forward time-velocity integral. Aortic forward stroke volume was calculated by multiplying aortic annular area with aortic annular time-velocity integral. In the absence of aortic regurgitation or shunt flow, the regurgitant stroke volume \( (SV_{Rg}, \text{cm}^3) \) was given by the difference between mitral \( (SV_m) \) and aortic \( (SV_a) \) forward stroke volume.\(^\text{18}\) Regurgitant fraction \( (RF) \) was calculated as \( RF = (SV_m - SV_{Rg}) / SV_m \).\(^\text{19}\) The mean regurgitant orifice area \( (ROAm) \) is calculated as the regurgitant stroke volume \( (SV_{Rg}) \) divided by the mitral regurgitant time-velocity integral \( (TVI_{Rg}) \) obtained from the continuous-wave regurgitant velocity spectrum: \( ROAm = SV_{Rg} / TVI_{Rg} \).\(^\text{21}\)

**Statistics**

**In vitro study.** The effective ROA \( (ROAp) \) calculated by the proximal flow convergence method and the true effective ROA were compared using linear regression analysis, and a correlation coefficient was calculated. The difference between the calculated and true effective ROA \( (ROAm) \) was calculated and expressed as mean difference ± SD.

**Clinical study.** For the patient data, ROA calculated by the proximal flow convergence method \( (ROAp) \) was correlated with regurgitant orifice area \( (ROAm) \) obtained by the pulsed Doppler method. The difference between the effective ROA calculated by the proximal flow convergence method and the Doppler echocardiographic method \( (ROAp - ROAm) \) was calculated and expressed as mean difference ± SD. ROAp was also compared with Doppler-derived regurgitant stroke volume and regurgitant fraction by linear regression and with the angiographic grade of mitral regurgitation by Spearman rank correlation.

**Results**

**In Vitro Study**

The flow rates investigated in this study ranged from 23.3 to 245 cm/s, with peak velocities ranging from 190 to 510 cm/s. The flow rates calculated based on the automated analysis of the proximal flow convergence zone \( (y, \text{cm/s}) \) showed an excellent agreement with the true flow rates \( (x): r = .991, y = 0.99x + 0.83, \Delta y = -4.3 ± 8.5 \text{ cm/s}. \) The calculated effective ROAs \( (ROAp) \) by the proximal flow convergence method ranged from 5.5 to 63.7 mm². The calculated ROAm \( (y, \text{mm}) \) correlated very closely with the true effective regurgitant orifice area \( (ROA)(x): r = .992, y = 0.92x + 1.0, \text{ as shown in Fig 3. The difference between calculated and true ROA \( (ROAp) \) minus true ROA was } \Delta = -1.4 ± 2.9 \text{ mm²}. \) ROAm was calculated for each orifice size throughout a range of different hemodynamic conditions. The accuracy of ROAm calculations was independent of the driving pressures for all orifices tested \( (P=NS) \) (Fig 4).

**Clinical Study**

For all study patients, the peak regurgitant flow rates \( (Q_p) \) calculated by the proximal flow convergence method ranged from 12 to 372 cm³/s \( (80 ± 98 \text{ cm³/s}) \) and the peak regurgitant velocities \( (v_\phi) \) from 396 to 664 cm/s \( (490 ± 58 \text{ cm/s}) \). The effective regurgitant orifice area \( (ROAm) \) \( (y) \) calculated based on the analysis of the proximal flow convergence zone ranged from 3 to 78.
FIG 4. Line plot shows the accuracy of the effective regurgitant orifice area calculated by the proximal flow convergence method (Y-axis) throughout a range of different driving pressures (X-axis) for four different-sized circular orifices.

mm² (14±13 mm²) and correlated closely with regurgitant orifice area (ROAₚ) calculated by the Doppler echocardiographic method (x): r=.95, y=1.08x−1.4, as shown in Fig 5. The difference between ROAₚ and ROAₚ (ROAₚ−ROAₚ) is Δ=−0.2±3.9 mm². For the entire study population, ROAₚ showed good correlations with regurgitant stroke volume (r=.93, Fig 6) and regurgitant fraction (r=.82), obtained by the Doppler echocardiographic method. ROAₚ <10 mm² corresponded with regurgitant stroke volume 10.2±4.2 cm³ (mean±SD; range, 2.8 to 22.2 cm³) and a regurgitant fraction 0.19±0.05 (mean±SD). ROAₚ ≥30 mm² corresponded with regurgitant stroke volume 67.6±15.9 cm³ (mean±SD) and regurgitant fraction 0.62±0.14 (mean±SD). For a subgroup of 20 patients who underwent cardiac catheterization, ROAₚ correlated well with the angiographic grade of mitral regurgitation (ρ=.81) by Spearman’s rank correlation. Patients with grade I mitral regurgitation had an effective ROA <10 mm²; grade II mitral regurgitation corresponded with ROAₚ between 10 and 25 mm², and patients with grade III mitral regurgitation had ROAₚ >25 mm².

FIG 5. Line plot shows the correlation between effective regurgitant orifice area calculated by the proximal flow convergence method (Y-axis) and the Doppler echocardiographic method (X-axis) in the clinical setting of mitral regurgitation.

FIG 6. Line plot shows the correlation between effective regurgitant orifice area calculated by the proximal flow convergence method (Y-axis) and regurgitant stroke volume obtained by the Doppler echocardiographic method (X-axis) in 77 patients with mitral regurgitation.

Discussion

The hemodynamic assessment of valvular regurgitation remains largely limited to a semiquantitative grading of invasive or noninvasive parameters that have shown some correlation with the regurgitant volume.1-5 Also, the quantitative angiographic technique or the recently introduced quantitative color Doppler flow methods calculate regurgitant stroke volume, regurgitant flow rate, or regurgitant fraction.7-12 However, analogous to pressure gradients in the assessment of stenotic valvular lesions, regurgitant volume reflects not only the intrinsic severity of the regurgitant lesion but also will be significantly affected by changing hemodynamics. For stenotic lesions, the assessment of orifice area has been shown to be a fundamental parameter for the serial evaluation of its severity, since changes in orifice area reflect true changes in valvular geometry.22,23

In this study, we introduce the concept of effective ROA as a fundamental parameter in the assessment of valvular incompetence. Unlike stenotic valve area, ROA has never been widely used in clinical practice. Recently, however, the proximal flow convergence method has been proposed as a promising technique to quantitate regurgitant lesions. This approach not only allows one to calculate regurgitant stroke volume and regurgitant flow rate, but ROA can also be easily obtained. By the principle of conservation of mass, the instantaneous orifice flow rate can be calculated based on the analysis of the converging flow field proximal to the orifice. The effective ROA is then simply given by dividing the orifice flow rate by the orifice velocity, measured by continuous-wave Doppler. In the current study, we validated this theoretical concept in an in vitro model and evaluated the accuracy of the orifice area calculations for a series of different sized circular orifices throughout a range of clinically relevant driving pressures. To validate this concept clinically and investigate the size and range of ROAs in mitral regurgitation, we calculated the effective ROA in 77 patients with mitral regurgitation. In a subgroup of 54 patients, we have shown previously the feasibility and the accuracy of the proximal flow convergence method to calculate regurgitant stroke volume and regurgitant flow rate.15
Results of the Current Study

The in vitro study shows that the effective ROA calculated based on the analysis of the proximal flow convergence zone displayed by color Doppler flow mapping is feasible and correlates very closely with the true effective regurgitant orifice for a range of different orifice sizes as shown in Fig 3. The study also shows that the accuracy of the ROA calculated by the proximal flow convergence method is independent of the driving pressure (P<.1) in the range studied (Fig 4).

To apply this method in the clinical setting, we calculated effective ROA based on the analysis of the proximal flow convergence zone in 77 patients with mitral regurgitation. The effective ROA in our study population ranged from 3 to 78 mm² (14±13 mm²). This calculated ROA by the proximal flow convergence method correlated very well with the ROA obtained by the Doppler echocardiographic method. The calculated ROA also correlated well with other quantitative measures of regurgitation obtained by Doppler echocardiography: regurgitant stroke volume (r=.93), regurgitant fraction (r=.82), and semiquantitative grading of mitral regurgitation by left ventriculography (ρ=.81). It should be recalled, however, that these latter parameters not only reflect the morphological severity of a regurgitant lesion but are also significantly affected by the hemodynamic conditions. We believe that the ROA is a more fundamental parameter and uniquely reflects the severity of regurgitant lesions largely independent of hemodynamics.

The present study suggests that an effective ROA of <10 mm² corresponds to a mild mitral regurgitant lesion; all patients with ROAp <10 mm² had a regurgitant fraction of <0.30 (0.19±0.05) by Doppler echocardiography and grade 1 mitral regurgitation by left ventriculography. An ROAp between 10 and 30 mm² coincides with moderate mitral regurgitation. An ROAp ≥30 mm² suggests a severe mitral regurgitant lesion confirmed by the angiographic grade III of mitral regurgitation and the Doppler echocardiographic measures: regurgitant stroke volume >50 cm³ (67.6±15.9 cm³) and regurgitant fraction 0.62±0.14.

Compared with other studies, the peak regurgitant flow rates calculated by the proximal flow convergence method in patients with severe mitral regurgitation in our study are lower than the values observed by other investigators who reported peak instantaneous regurgitant flow rates over 1000 cm³/s. This may be due in part to the fact that in our study population, we have not observed any patients with acute severe mitral regurgitation caused by ruptured chordae or leaflet flail. However, we believe that these high flow rates may reflect an overestimation of flow calculated by the proximal flow convergence method that may be multifactorial in origin: (1) in the presence of leaflet flail, flow may converge over less than 180°, resulting in an overestimation of flow when a hemispheric shape of the converging flow field is assumed, (2) selection of a high wall filter will increase Doppler velocities in the proximal flow convergence, and (3) the presence of outflow may distort the lowest baseline-shifted velocities and will result in an overestimation of the calculated flow rates.

Limitations and Future Directions

In the controlled environment of an in vitro setting, we found an excellent correlation between true effective ROA and the effective ROA calculated based on the analysis of the proximal flow convergence zone for circular orifices with planar surroundings. We applied this theoretical concept in the clinical situation of mitral regurgitation, where peak regurgitant flow rate was calculated at a single isovelocity contour assuming hemispheric symmetry of the proximal flow field. This approach inherently has the limitations of the proximal flow convergence method, for which previous numerical and in vitro studies have warned. First, in the immediate vicinity of the regurgitant orifice, the isovelocity contours flatten out, causing progressive underestimation of flow and subsequently calculated ROA, if a hemispheric shape is assumed. We have shown previously that the underestimation (as a proportion of actual flow) is roughly equivalent to the ratio of the aliasing velocity of interest to the peak orifice velocity (ie, v/νp) and can be corrected for by a simple correction factor (multiplying calculated flow by 1/v/νp+[v/νp]). In the clinical study, all of the aliasing velocities were baseline-shifted to <10% of νp, most <5%, and thus no correction was applied. Baseline shifting has the additional advantage of increasing the isovelocity radius so that proportional errors in measurement are reduced.

The second potential error in assuming hemispheric isovelocity contour shape for flow rate and orifice area calculations is when the orifice lies in a nonplanar surface. We have shown that when the orifice lies in a funnel, the constant 2π in the flow equation must be reduced to reflect the solid angle subtended by the funnel. Conversely, if the orifice were at the tip of an inverted funnel (eg, incomplete mitral valve closure), the constant would be expected to be larger than 2π. Although this error remains a theoretical concern, it did not appear to be of sufficient magnitude to significantly affect effective ROA calculations in this study. It should be noted that our patients with mitral regurgitation were without ruptured chordae or flail leaflets that might be particularly prone to this kind of error. However, global geometry may be different for different types of valves and may become more important when effective ROA is calculated for other regurgitant lesions. Further study certainly is needed.

The third potential error may result from technical difficulties in clinically implementing the proximal acceleration method. It is straightforward to detect the isovelocity contour of interest, but the location of the orifice is often more elusive. A small error in localizing the orifice will seriously affect the flow rate and orifice area calculations. In our in vitro experiments, we used an algorithm that uses the full digital velocity map of the proximal flow field to identify the orifice center and automatically calculates the instantaneous regurgitant flow rate. The location of the regurgitant orifice is determined assuming flow convergence toward an infinitesimal orifice where the anatomic and effective orifice location coincide. For flow converging toward a finite orifice, the location of the effective orifice or the vena contracta is slightly downstream from the anatomic orifice location. Although this difference is small, it may lead to underestimation of the radial distance to isove-
loicity contours close to the orifice; however, the impact on the radius measurements to distal isovelocity contours and the subsequently calculated flow rates appear to be minimal.\textsuperscript{16} Validation of such an algorithm clinically would allow the proximal convergence calculation to be made routinely in echocardiographic practice.

Finally, it must be noted that the ROA calculated by the proximal flow convergence method represents a midsystolic effective ROA, assumed to coincide with peak regurgitation. This orifice area closely correlates but is not necessarily exactly the same as the ROA calculated by the Doppler echocardiographic method, which represents a mean effective ROA. In one study, dynamic changes of the ROA during systole were observed in an animal model of mitral regurgitation where a gradual decrease in ROA throughout the systolic time interval was observed.\textsuperscript{27} A preliminary clinical study using color Doppler M-mode also suggests the presence of dynamic changes of the ROA during systole.\textsuperscript{28} Future study may investigate in more detail the relation between the midsystolic and mean effective ROAs. Since the proximal flow convergence method calculates instantaneous ROAs, this approach would allow us to study dynamic changes in effective ROA during the systolic time interval.

Conclusions

The effective ROA is a fundamental parameter in the assessment of valvular incompetence that provides unique information on the severity of regurgitant lesions independent of hemodynamic conditions. In this study, we propose the theoretical concept and provide the methodology to calculate noninvasively the effective ROA, based on the analysis of the proximal flow convergence zone. This theoretical concept was validated in a series of in vitro experiments and applied in the clinical setting of mitral regurgitation. The ability to calculate ROA should enhance our understanding and improve the serial assessment of valvular insufficiency.

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