EDITORIAL COMMENT

Interaliasing Distances to Assess Mitral Regurgitation: Dividing the Rainbow of Flow Convergence*

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Accurate quantification of mitral regurgitation was of limited need when surgery was considered only for patients with significant symptoms. Advances in surgical technique and perioperative patient management have reduced the risk of mitral valve surgery. Meanwhile, patients are recommended for mitral valve repair at an earlier stage in the natural history of mitral regurgitation when they are only mildly symptomatic and before left ventricular dysfunction occurs. To pursue the concept of early intervention and enable appropriate timing of surgery, a significant need exists for a diagnostic modality allowing accurate evaluation of the volumetric mitral incompetence and that is easily applicable in clinical practice. Subjective, categorical assessment of the severity of valvular insufficiency as mild, moderate or severe using color Doppler echocardiography is still being used in a large proportion of clinical practice. This method, which is based on the evaluation of the flow jet in the receiving chamber, has important limitations because the spatial jet distribution is significantly affected by both instrumentation and hemodynamic factors (1).

Various echocardiographic techniques have been proposed for improved quantification of valvular incompetence. Among these, the proximal flow convergence method using color Doppler is accepted as a reliable and accurate quantitative approach.

PROXIMAL FLOW CONVERGENCE METHOD

The basis of the proximal convergence method is the conservation of mass, with the assumption that, in the region proximal to a regurgitant orifice, flow is laminar and accelerates smoothly, forming concentric shells of increasing velocity and decreasing surface area. Both in vitro and clinical testings have confirmed isovelocity contours for small orifices in flat surfaces to be of hemispheric shape (2,3), allowing the evaluation of flow rate through the regurgitant orifice as: flow rate = 2πr²V where r is the distance to the contour defined by the change in color at the aliasing boundary and V is the aliasing velocity. The advantage of the accelerating flow field is its hydrodynamically more stable, laminar flow compared to the decelerating jet within the left atrium, which has more turbulent flow characteristics. Because of the centralized flow distribution in the region proximal to the orifice, the degree of regurgitation can be accurately predicted with this method even when an eccentric jet or a regurgitant jet is impinging on a wall surface.

Clinical validation studies early in the evaluation of the flow convergence method confirmed a high correlation of proximal isovelocity surface area (PISA) estimates of regurgitation with angiographic degree of regurgitation (r = 0.87 to 0.91) (2,4). In addition to assessment of regurgitant flow rate and regurgitant volume, the proximal flow convergence method has been used to calculate the effective regurgitant orifice area of incompetent valves. This can be achieved by dividing the peak flow rate by the maximal velocity through the orifice obtained by continuous-wave Doppler. Analogous to the stenotic orifice area for the assessment of valvular stenosis, the regurgitant orifice area represents a fundamental parameter to define valvular insufficiency largely independent of hemodynamic conditions. The PISA-derived mitral regurgitant orifice area estimates have been validated over a broad spectrum of clinical circumstances (5,6). Use of the concept of proximal flow convergence has been widened by application to other clinical circumstances involving a restrictive orifice. In particular, it has been used to evaluate valvular regurgitation affecting the tricuspid or aortic valve, to assess the valvular area in mitral stenosis, to determine the severity of obstruction in aortic coarctation and to measure the shunt flow in ventricular or atrial septal defects (7–9).

However, important problems and pitfalls can be defined in the application of the proximal flow convergence methodology for quantitative assessment of valvular regurgitation severity. The theoretical assumption that the proximal flow convergence region consists of a series of hemispheric surfaces does not fit for the practical situation where the shapes of the isovelocity surfaces change based on the flow rate, orifice size and aliasing velocity such that applying the simple hemispheric flow convergence equation to calculate flow rates may well overestimate or underestimate actual flow rates (10).

Most of the difficulties of the flow convergence method relate to the geometry of the flow convergence zone. To understand the limitations of the flow convergence method, the concept of the “developing proximal flow field” is critical. The assumption that the PISAs are always hemispheric is not valid. Rather, it is that the proximal flow field alters from an essentially laminar flow in the body of the

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ventricle to a hemispheroidal and, further on, a truly hemispheric flow shape when lateral forces entrain it toward the orifice and there is a final progressive flattening near the orifice (3). Due to the changing pattern of flow, the position chosen for the PISA estimation is critical for accurate quantification of regurgitation. This results in overestimation of flow rate if the alias velocity is used where the flow field is still hemispheroidal and underestimation of flow if the aliasing velocity is estimated in greater proximity of the regurgitant orifice. For the same orifice size and flow rate, displayed PISA shape is a flat hemi-ellipse at high blue-red interface velocities and nearly hemispheric at lower blue-red interface velocities. For the same flow rate and color Doppler blue-red interface velocity, displayed PISA shape is a flat hemi-ellipse for larger orifice sizes and nearly hemispheric for smaller orifice sizes.

Furthermore, the assumed hemispheric contour of the flow convergence zone can be significantly affected by the inlet geometry. In particular, alterations in the leaflet angle have an important impact on the calculated regurgitant volumes, whereby a reduced inlet angle results in overestimation of regurgitant flow. Correction factors that account for the inlet angle have been applied. Whereas irregular or deformed orifices, instead of the assumed circular orifice, have been shown not to be significant sources of inaccuracy, dynamic variation in regurgitant orifice diameter over the cardiac cycle further complicates the clinical application of the PISA methodology. Usually the frame demonstrating the largest visual area of flow convergence is used for analysis. This allows an estimate of the peak flow rate but not absolute flow, as flow rate will vary throughout the cardiac cycle. Thus, the regurgitant flow estimated by the PISA method tends to overestimate the true mean flow rate in situations of dynamic orifice alteration.

A major limitation of the proximal convergence method to assess regurgitant flow rate is related to the need to define with accuracy the regurgitant orifice level. Determination of the regurgitant orifice level can be difficult, in particular as the position of the regurgitant orifice may change during the cardiac cycle. Minor inaccuracies in the definition of the regurgitant orifice level result in imprecise determination of the radius of the hemispheric contour. Significant inaccuracies of the calculated regurgitant volume may be the consequence. The difficulty to define with accuracy the orifice level has been addressed before by attempts to circumvent the need for orifice-level determination. Vandervoort et al. (11) proposed an automated algorithm that allows the calculation of flow rates based on digital Doppler velocity maps. This algorithm helps in the estimation of the position of the regurgitant orifice. The method suggests that, in a region of flow convergence at a distance from the regurgitant orifice, it is possible to generate a “theoretical flow field” by computer simulation. Multiple theoretically predicted velocity distributions are generated and compared with the observed velocity field by Doppler color flow mapping. The derived velocity field that most closely equals the observed velocity field is used to estimate the position of the regurgitant orifice. Thus, the algorithm allows the localization of the effective regurgitant orifice and subsequent calculation of regurgitant flow rate and effective regurgitant orifice area. However, due to the complexity of the model, it has not found clinical application.

In clinical practice, potential errors in estimating the radius of the isovelocity hemisphere have been reduced by evaluating an aliasing contour located more distant from the orifice. Altering instrumentation settings to allow the first alias to occur as far from the orifice as possible can be achieved simply by changing the color baseline shift. While the first aliasing limit is decreased by zero-shifting the velocity cutoff, the radial distance (r) between the first alias and the regurgitant orifice increases exponentially.

**IMAGING OF INTERALIASING DISTANCES**

In an attempt to address the difficulties in accurately determining the distance between the valve orifice level and the first aliasing contour, the interaliasing distances (IADs) method reported by Sitges et al. (12) in this issue of the *Journal* is proposed. Instead of measuring the radius of the first aliasing boundary, the radius is calculated from the distance between the first and second aliasing contour. This obviates the need to determine the mitral valve orifice level and thereby circumvents one important difficulty resulting in inaccurate evaluation of the size of the proximal flow convergence zone. The theory behind the use of the IAD is straightforward and based on sound physical principles. The fact that the technique can potentially be performed semi-automatically increases its attractiveness. The IAD method requires precise determination of the distance between the first and second aliasing border. The baseline shift of the color Doppler velocity has to be set at zero to allow application of the fundamental equation where the flow convergence radius \( r_{calc} \) can be calculated from the IAD times 3.41 (\( r_{calc} = \text{IAD} \times 3.41 \)). The calculated flow convergence radius is subsequently used for determination of regurgitant volume and regurgitant orifice area in a similar way than the measured flow convergence radius obtained in the conventional application of the method. To account for the small absolute distances, which ranged between 1.0 and 2.5 mm in this study (12) and to improve the accuracy, the zoom mode was applied to magnify the distance and at least three measurements were averaged. Furthermore, color Doppler M-mode recordings are applied to a central scan line to allow greater accuracy in the measurement of the interaliasing distance. The investigators nicely validated the IAD method in an animal model using 39 different hemodynamic conditions and orifice areas ranging from 1.9 to 31.4 mm². Calculated mitral regurgitant volumes from the IAD method showed a high correlation with those determined by electromagnetic flow meters.

Whereas interest in the flow convergence method has been focused on the first aliasing border, the second
third aliasing radii of the flow convergence zone have been used before for analysis of the regurgitant volume (13). The radii of the second and third aliasing boundaries decrease exponentially. Zhang et al. (13) used multiple aliasing boundaries to analyze the shape of the proximal flow convergence region and the impact of different isovelocity distances on the calculated flow rates. Striking differences in the calculated flow rates could be demonstrated. For the first aliasing boundary, which is most distant from the regurgitant orifice, there was an overestimation of regurgitant flow by 151%; for the second aliasing boundary this was 7%; and for the third aliasing boundary, which is least distant from the orifice, there was an error of −43%. This was found to accord with the theory that isovelocity contours distant from the orifice overestimate flow due to the hemielliptic contour, and isovelocity contours proximal to the orifice underestimate flow because of the flattened contour. The IADs method is an extension of the use of the second aliasing boundary for regurgitant flow assessment. Analyzing the IAD, which covers a broader band within the flow convergence field, instead of the thin shell of the first aliasing border might have a potential advantage with respect to resemblance of the analyzed flow convergence region to a hemisphere.

**POTENTIAL PROBLEMS**

Although promising results could be demonstrated in the Sitges et al. (12) article in this issue of the Journal, there is the need to validate further the method in clinical practice, demonstrating different valve pathomorphology. Several of the before-mentioned problems related to the flow convergence zone are likely to also affect the measurement of IADs. Additional difficulties may endanger the accuracy of this new modality. Given the small IADs, the use of M-mode color Doppler seems to be necessary to obtain a high spatial resolution. However, M-mode color studies have been shown to have important limitations in the assessment of optimal versus nonoptimal shape of the flow convergence zone. Flow convergence zones are frequently not hemispheric in cases of distorted mitral valves with asymmetric valve morphology. This may increase difficulties in accurately determining IADs, especially as the M-mode color Doppler has to be applied to the central scan line.

Translation movements of the heart may affect the alignment between the M-mode line and the real center line of the flow convergence region. Underestimation of IADs and, subsequently, regurgitant volumes might be the consequence as noted by the investigators (12) and may have a greater impact on the accuracy of the method in the clinical setting than in the setting evaluated in this study.

Another important problem relates to the fact that the flow convergence zone is not hemispheric at all distances from the regurgitant orifice. However, though the distance from the regurgitant orifice to the first aliasing contour can potentially be altered using the color Doppler baseline shift to get the isovelocity surface of the first aliasing border to a distance where the flow convergence zone is hemispheric, the zero baseline shift cannot be applied with the IAD method.

An additional difficulty of the method relates to the small dimensions of the IAD. Interaliasing distances are only 1/3.41 of the conventionally measured radius of the PISA method using the first aliasing velocity. Furthermore, the radius of the hemisphere of the first aliasing velocity can be increased by zero-shifting the Doppler velocity cutoff, allowing greater accuracy in the radius measurement and subsequently higher accuracy of the calculated flow rate through a flow convergence region. However, it is not possible to stretch the IAD by using a baseline shift of the color Doppler velocity map, as the second aliasing velocity would no longer be twice the first aliasing velocity, a fundamental basis for application of the method. Thus, IADs can be expected to be even <1/3.41 of the radius measured while applying the conventional flow convergence method.

In clinical practice, IADs of only 1 to 3 mm have to be expected, indicating the small absolute dimensions and also the small difference between the IADs of minor and severe regurgitation. For a flow rate of 75 cc/s and an aliasing velocity of 38 cm/s, the IAD would be 1.64 mm, whereas for a flow rate of 250 cc/s and the same aliasing velocity the IAD would be 2.99 mm. Thus, a mere 1.35 mm would differentiate between a moderate and a severe mitral regurgitation.

In contrast, the radius of the flow convergence technique would be 5.6 and 10.2 mm for the two flow rates, respectively. In the chosen case of a flow rate of 75 cc/s and an aliasing velocity of 38 cm/s, overestimation of the radius by 1 mm would result in a calculated flow rate of 104 cc/s (overestimation by 38%), whereas overestimation of the IAD by 1 mm would result in a calculated flow rate of 193 cc/s (overestimation by 158%), indicating that the small IADs offer a source for significant measurement inaccuracies. Considering this background it will be important to evaluate further the reproducibility of flow data obtained by the IADs method under clinical conditions.

The investigators (12) claim that current techniques of flow convergence evaluation are not used in clinical practice owing to the time-consuming nature of their application. They conclude that there is a need for a method which is easier to use. However, it has to be determined whether the IADs method will find greater acceptance, as color Doppler M-mode has to be applied as an additional step to the conventional PISA technique to obtain the radius of the first aliasing border.

Considering these shortcomings, clinical application studies will show whether the method can be recommended for routine clinical use. Moreover, these limitations portend important obstacles of the method to replace the conventional flow convergence method. However, the IADs method may become an alternative in cases that do not...
allow accurate application of the PISA technique due to difficulties in the determination of the regurgitant orifice level. This may also apply to the assessment of valvular regurgitation in patients with valve replacement. Especially in these patients, definition of the regurgitant orifice level is frequently very difficult and does not allow application of the conventional PISA methodology.

CONCLUSIONS

The measurement of IADs provides a new echocardiographic technique based on the flow convergence method for quantitative assessment of mitral regurgitation. Considering the need for accurate quantitative evaluation of valvular incompetence, this method represents a valuable addition to the existing modalities, one that can be used in cases where it is difficult to apply already available techniques. The small dimension of the IAD requires very meticulous measurements to prevent inaccuracies. Thus, the method may become a useful adjunct, although it is unlikely to replace currently used flow convergence techniques. Further clinical evaluation will show whether the technique holds the promise of a simple, accurate, noninvasive, and quantitative marker of valvular regurgitation to be used in clinical practice.

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REFERENCES