The rapid realization that color Doppler flow mapping was not an “ultrasonic angiogram” has led to considerable interest and experimentation into the display characteristics of color flow mapping. This, in turn, has improved our understanding of the strengths and limitations of the technique. Accurate quantification of volume flow from color Doppler flow map images is notoriously difficult, particularly in patients with valve regurgitation, and it is the experimental evidence of color flow quantification in this area that has been most rewarding. The study by Ritto et al in this issue of Circulation has used this knowledge to apply quantitative color Doppler flow mapping in patients who have acquired an atrial septal defect (ASD) as a result of balloon mitral valvuloplasty.

The attraction of imaging the proximal zone of flow convergence has resulted from the difficulties of extracting quantitative information from the downstream jets imaged by color flow mapping in the receiving chamber distal to a restrictive orifice. There is a very sound hydrodynamic basis for the structure of jet flow within the heart that describes the formation of free jets, their velocity profiles, and the characteristics of their intrusion into the receiving chamber. The size of these jets on color Doppler flow mapping has been shown to be largely a function of flow rate through the orifice, but it is clear that the spatial distribution of intracardiac jets on color flow mapping is highly complex and significantly altered by the driving pressure acting on the jet, yet with relatively little effect from the volume of flow itself. As a velocity mapping technology, it is perhaps not surprising that the display characteristics of color Doppler flow mapping should be so heavily biased toward velocity assignment rather than volume flow. Not only have hemodynamic factors been identified as having a considerable effect on the display of color-encoded jets, but the alteration in jet appearance can also be dramatically affected by instrumentation factors. Enthusiasm for using the downstream color jets to make any accurate quantitative assessment of severity in valve regurgitation and shunt flow has largely been tempered by the substantial dependence of these jets on both instrumentation and hemodynamic factors, although sophisticated momentum analysis of the color-encoded jets may enhance the ability of color flow mapping to provide such quantitative information.

We had previously recognized that flow velocity information exists on the proximal side of a restrictive orifice, the so-called flow convergence zone, which could be imaged by color Doppler flow mapping. It was also shown that acceleration changes within this zone yielded quantitative information about obstructive lesions. However, the concept that this proximal flow convergence zone could be used to estimate volume flow through the orifice was first recognized by Recusani et al, and this principle forms the basis for the present study. The estimation of volume flow by this method is, like all good concepts, a relatively simple one and assumes that all the “flow” within the proximal flow convergence zone enters and subsequently passes through the restrictive orifice. If the flow in this region is assumed to be a series of isovelocity hemispheres, or shells, with smaller hemispheres of increasing velocity as flow approaches the orifice, then the flow rate through the orifice may be estimated as a function of the hemisphere area multiplied by its velocity. Theoretically, the result should be identical for any of the isovelocity shells within the flow convergence region. The area of the hemisphere can be easily calculated by measuring the radius of the hemisphere (r) from the restrictive orifice and incorporating this into the formula area = 2πr². Since the product of hemisphere velocity and its area should be the same no matter which hemispherical area is used, the hemisphere associated with the first or second color alias allows accurate determination of the true velocity value and is sufficiently distant from the orifice to minimize error in the measurement of the hemisphere radius. Unlike the jet produced in the receiving chamber, which is decelerating and highly turbulent, the zone of flow convergence is a region of accelerating flow and, as such, is more stable laminar flow. This region is thereby more suited to quantitative velocity determinations.

The authors of the present study have applied this flow quantification concept to patients with an ASD created at the time of balloon mitral valvuloplasty using biplane transesophageal echocardiography (TEE). Aside from the dramatically improved image quality of the TEE images, the higher-frequency transmitted ultrasound produces a lower aliasing color velocity value. This has two effects. First, it allows color encoding of lower-velocity flow within the atrium, and this results in

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an enlarged visual appearance of the flow convergence region. In addition, the color alias occurs at a somewhat larger distance from the restrictive orifice and thereby improves the accuracy of the radius measurement. This latter effect can also be achieved by zero-shifting the baseline velocity value of the color flow map, but the improved spatial resolution of the higher-frequency TEE imaging is advantageous for color quantification purposes. Using the hemisphere at the velocity shell demarcated by the first or second alias allows accurate estimation of the hemisphere velocity, since this is simply the Nyquist velocity value.

In the present study, 36 patients were studied after balloon mitral valvuloplasty and divided into two groups on the basis of oximetry analysis. Group 2 consisted of 11 patients in whom a left-to-right shunt could be detected with oximetry. In these patients, the maximum flow rate across the restrictive ASD as estimated from the flow convergence region was matched by a relatively close correlation with shunt flow calculated by oximetry. In the remaining 25 patients without a detectable shunt on oximetry (group 1), transesophageal imaging and color flow mapping were able to detect a shunt at atrial level in 22 patients, highlighting the relative insensitivity of oximetry for the detection of small shunts and the high sensitivity of color flow mapping for the detection of intracardiac flow velocities. When the authors examined the results for maximum flow rate across the defect, there was no overlap between the two groups, with a flow rate of 20 mL/sec indicating the presence of a detectable shunt with oximetry. A region of proximal flow convergence could not be detected in two of the patients in group 1 who did have a detectable shunt by other color flow mapping criteria. One must assume that these two patients had very small shunts insufficient to produce even a small zone of proximal flow convergence within the resolution of the system.

Using a combination of the maximum flow rate estimated from the flow convergence region and the peak velocity across the ASD, as measured by high pulse repetition frequency Doppler echocardiography, the authors were also able to estimate the functional flow area of the defect and correlate this with the anatomic defect area imaged by transesophageal echocardiography, presenting a close relation between the two techniques ($r=0.93$). The accuracy of this estimation must be questioned to some extent, since the assumption that the ASD was elliptical when two ultrasound views were obtained and circular when only a single imaging plane was possible is practical if not necessarily accurate. Although a good correlation was obtained between the two methods, it is noteworthy that the majority of the cases had very small defects (<10 mm²), with only a few patients demonstrating larger defects. This favors a statistically good correlation without necessarily representing an acceptable level of clinical accuracy though the authors have shown this to be the case in only one of their patients who had a septal defect of unusual geometry.

At face value, noninvasive estimation of flow rate and orifice area in ASDs after balloon mitral valvuloplasty would appear to represent useful information, yet the clinical value and relevance must be questioned. The size of the ASD caused by balloon mitral valvuloplasty is almost always small, particularly since the widespread use of the Inoue balloon technology. Identifying the presence of an ASD in this situation and quantifying the flow across it by TEE is unlikely to provide practical clinical information, since the majority of these septal defects close spontaneously in the 6 months after valvuloplasty, and those that remain are generally small. Importantly, the technique as described will not be applicable to large, unrestricted ASDs in which shunt quantification may be of clinical importance, since the nature of the proximal zone of flow convergence is a function of the presence of a restrictive orifice, and in this setting no such region will be detectable. The real value of this study is not its clinical application in ASDs but rather its contribution to expanding the validity of using the flow convergence region on color flow mapping as imaged by TEE to estimate flow rate and functional flow area. There is increasing evidence that quantitative information can be gained from this flow convergence region proximal to a restrictive orifice in other clinical circumstances. In patients with congenital heart disease, quantitative information on severity of obstruction in aortic coarctation has been reported, and in ventricular septal defects, the use of the flow convergence region to quantify shunt flow has produced results similar to those of the present study.

Several assumptions have been made in the use of the proximal flow convergence zone methodology. First, the question of orifice shape arises. Much of the in vitro investigation of flow convergence has used a circular orifice, but, as the authors of the present study suggest, there is some evidence that the hemispherical method of flow quantification is valid for both circular and elliptical orifices. The increasing clinical application of this methodology in valve regurgitation would tend to confirm this accuracy despite irregular or deformed orifices. The second and more important assumption is that the flow convergence region is hemispherical. Computer modeling and in vitro testing have demonstrated that as the isovelocity hemispherical shells approach the restrictive orifice, they tend to flatten, and if a hemispherical area is assumed to be present at this point, there will be a tendency to underestimate true flow rate. Subsequent in vitro comparisons of color flow mapping with phase velocity encoded magnetic resonance imaging have suggested that the flow convergence region is close to hemispherical at between one and three orifice diameters from the restrictive orifice. As a result, it is probably more valid to use the position of the second alias on color Doppler flow map images of the flow convergence zone to ensure a near hemispherical velocity shell rather than the first alias as used in the present study. When color Doppler flow mapping is used to quantify flow from the spatial velocity changes in the flow convergence region, it is often the frame demonstrating the largest visual area of flow convergence that is used. As with the present study, this allows an estimation of peak flow rate but not absolute flow, since flow rate will vary throughout the cardiac cycle. The use of flow rate may correlate well with shunt or regurgitant volume flow, but it should be recognized that to obtain actual shunt flow or regurgitant flow volume, one must take into account the temporal changes in flow rate throughout the cardiac cycle. It may be possible to achieve this by use of color M-mode technology combined with color flow mapping to estimate true volume flow by temporal and spatial averaging of flow rate over the cardiac cycle.
The value of using the flow convergence region in preference to the size of the jet in the receiving chamber is highlighted in the present study, in which the jet of atrial septal flow in the right atrium could not be fully characterized in five patients, mainly because of interference from the jet of tricuspid regurgitation. It is particularly noteworthy that, although the size of the jet was greater in group 2 than group 1, there was considerable overlap between the groups, whereas clear separation was obtained when the flow rate calculated from the flow convergence region was used.

The high sensitivity of color Doppler flow mapping for high-velocity flow through restrictive orifices and the improved spatial resolution of transesophageal imaging make the combination of techniques ideal for the clinical evaluation and application of quantitative analysis of the flow convergence region proximal to a restrictive orifice. Unlike the color-encoded jets within the receiving chamber, the zone of proximal flow convergence is much more laminar and thereby more suitable for quantification. Additionally, it is unlikely to impinge on the chamber walls or interact with other jets, as is true of the receiving chamber jets. Since color flow mapping will accurately encode the representative pixel velocity value, the region of the first or second alias in the flow convergence region will be relatively unaffected by gain and other instrumentation settings to which the receiving chamber jets are notoriously sensitive. As more clinical evidence accrues to support the value of flow quantification from the zone of proximal flow convergence and advancing imaging technology combined with the facility for digital acquisition and analysis of color Doppler flow map images allows more accurate quantitative determinations to be made, the flow convergence region may finally prove to be the pot of gold at the end of the quantitative color rainbow.

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