DOPPLER ECHOCARDIOGRAPHIC ASSESSMENT OF VALVAR REGURGITATION

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Improvements in outcomes for heart valve surgery, in particular mitral valve repair, have dictated a need for better assessment of valvar regurgitation. Whereas in the past surgery was delayed until the patient's symptomatic status required intervention, patients today are often sent to the operating room while still asymptomatic or minimally symptomatic. Before committing an asymptomatic patient to open heart surgery, however, it is essential that the severity of valvar regurgitation be quantified to ensure the surgery is actually required. Doppler echocardiography has emerged as the premier way of assessing valvar regurgitation, as it allows characterisation of valve morphology, severity of regurgitation, and secondary effects, such as left ventricular dysfunction, left atrial enlargement, and pulmonary hypertension. This review will outline current methods available to the echocardiographer in assessing valvar regurgitation, focusing on simple practical ways that true quantitative information can be obtained in a clinical laboratory. Techniques that are generally applicable in all forms of valve regurgitation will be introduced first, followed by specific techniques for mitral and aortic regurgitation.

COLOUR JET AREA METHOD

The most common way of assessing the severity of valvar regurgitation is to inspect the area of the colour Doppler jet in the downstream chamber.[1] The advantage of this approach is that it is fast, easy, and also provides information on the mechanism of regurgitation, as the jet is generally directed away from the most severely affected leaflet. However, jet area alone is impacted by many factors other than regurgitant flow rate, and an understanding of these will aid in its utilisation.

Determinants of colour jet Doppler area

The physical parameter that is most predictive of the size of a regurgitant jet by colour Doppler is jet momentum, given by the product of regurgitant flow rate multiplied by velocity.[2] Since jet velocity is directly related to the driving pressure across a regurgitant orifice (by the Bernoulli equation), the patient's blood pressure will have an important impact on jet size and so should be recorded at the time of the echo examination. Chamber constraint is the second major factor determining jet size. Obviously a jet, which is directed centrally into the left atrium, cannot extend further than the superior wall of the atrium, but chamber constraint is even more important for eccentrically directed jets that hug the chamber wall. In general, such a wall jet will appear much smaller (as much as 60% smaller) than the equivalent centrally directed jet because it is flattened against the wall and cannot recruit stagnant flow into the jet from all sides the way a centrally directed jet can.[3] The final factor impacting colour jet area size is the instrumentation set-up of the echocardiograph.[4] Increasing either the transmitted power of the instrument or the receiver gain will result in a larger jet, as weaker echoes on the periphery of the jet are detected. In general, colour gain should be increased until random colour pixels begin to appear in the tissue and then the gain reduced just slightly. The scale of the colour Doppler display (determined by the pulse repetition frequency) can have a profound effect on jet size as low velocity motion at the periphery of the jet will be encoded at low scales. Figure 1 shows how reducing the scale or Nyquist limit from 69 cm to 39 cm to 17 cm per second results in a dramatic increase in jet size.

For most purposes, the scale should be set at the highest limit allowed by the combination of imaging depth and interrogation frequency (and usually selected automatically by the instrument). Transducer frequency can have a dual effect on jet size. Because the Doppler shift is more profound at higher interrogating frequencies, jets tend to appear larger with higher frequency imaging. However, higher imaging frequencies are also prone to greater tissue attenuation and so the jets may appear smaller. In general, for transoesophageal imaging the Doppler enhancing effect of the higher imaging frequency dominates while for transthoracic imaging the attenuation factor predominates, causing jets to appear smaller at higher interrogating frequencies. Increasing the wall filter of the instrument will decrease the size of jets, by excluding velocities below a certain cutoff value, while increasing the ensemble length (sometimes referred to as the quality of the Doppler map) will yield a larger jet as lower velocities can be displayed by the finer colour maps.

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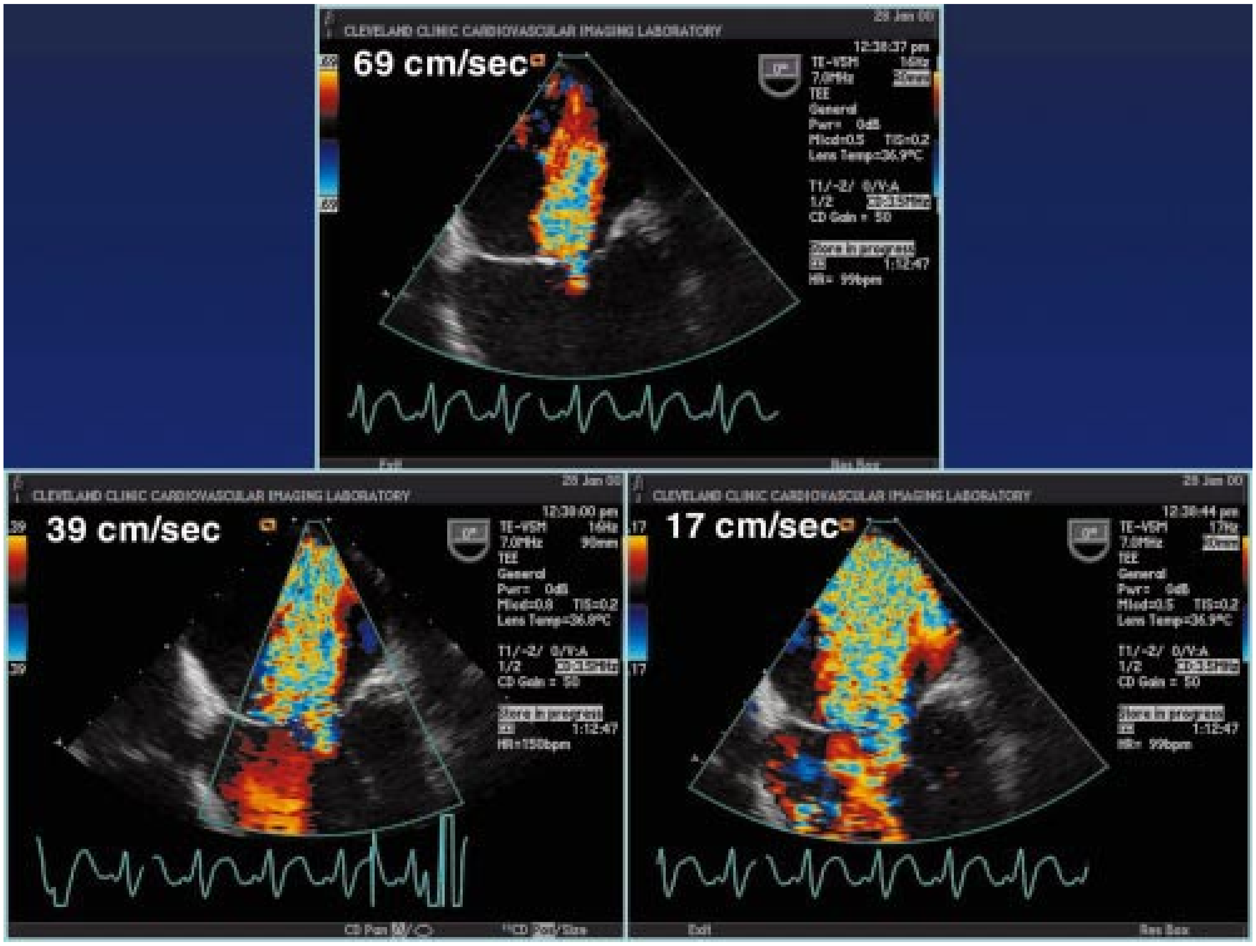

Figure 1 Impact of scale (pulse repetition frequency) on colour jet size. Because the colour Doppler processor records approximately 16 levels of red and 16 levels of blue, the lowest velocity encoded is approximately 1/16 of the maximal velocity. Thus the minimal velocities recorded in the above images are approximately 4 cm/s, 2 cm/s, and 1 cm/s as the scale is reduced from 69 to 39 to 17 cm/s.

The best rule of thumb is to standardise the instrument set-up within a given laboratory and leave these constant for all examinations. Unfortunately, regardless of the care that is taken in assessing the colour jet area, this method can only yield a semiquantitative assessment of regurgitant severity, with perhaps 4–6 distinct grades of severity detectable. Modern assessment of valvar regurgitation requires a more quantitative approach.

QUANTITATIVE TECHNIQUES

A variety of techniques have been described for the echo Doppler quantification of valvar regurgitation. Among the key parameters to be determined by these methods are the following:

- regurgitant volume, the amount of blood leaking through the valve in each cardiac cycle (given in ml)
- regurgitant flow rate, the maximal rate of leakage through the valve (given in ml/s)
- regurgitant fraction, the percentage of left ventricular stroke volume that leaks back through the valve
- regurgitant orifice area, the actual anatomic area of the regurgitant lesion and perhaps the best physical descriptor of valve disruption.

Volumetric approach to quantification

In general the approach to regurgitant quantification can be divided into two broad areas—volumetric assessment and direct assessment. The volumetric assessment relies on measuring stroke volume in two regions of the heart, one of which includes the regurgitant volume, the other of which includes only the systemic stroke volume.[5] The difference between these two stroke volumes is the regurgitant volume through the valve (fig 2). For example, in the case of mitral regurgitation, measuring stroke volume across the mitral annulus and left ventricular outflow tract and subtracting the latter from the former will yield the mitral regurgitant stroke volume. The stroke volumes can be obtained in a variety of fashions. Flow through the left ventricular outflow tract can be calculated by multiplying the area of the left ventricular outflow tract ($\pi D^2/4$, where D is the diameter of the left ventricular outflow tract measured just below the aortic valve in the parasternal long axis view) by the time velocity integral of the pulsed Doppler velocity measurement obtained in the same location. A similar approach can be used for measuring flow across the mitral annulus, by measuring the mitral annular area and multiplying this by the time velocity integral of the velocity obtained at that location. Alternatively, stroke volume can be obtained from two dimensional echocardiography by subtracting left ventricular end systolic volume from end diastolic volume, calculated by using Simpson's rule or the area–length formula from the left ventricular apex. It is also possible to obtain stroke volume in an automated fashion, by integrating colour Doppler velocities across the left ventricular outflow tract or mitral annulus throughout space and time.[6 7]

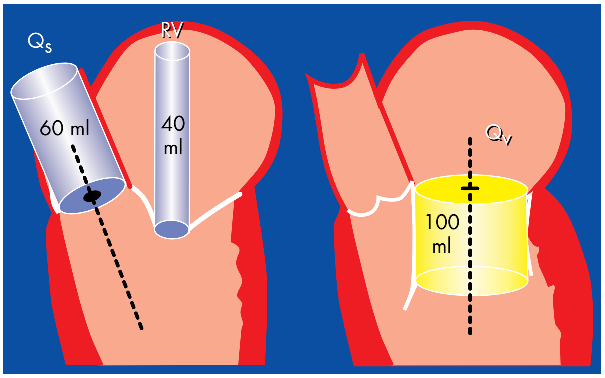

Figure 2 The principle of the volumetric assessment of valvar regurgitation. By measuring stroke volume in two areas of the heart, it is possible to use the difference between these to estimate regurgitant volume. Qs, systemic stroke volume; Qv, stroke volume across regurgitant valve; RV, regurgitant volume.

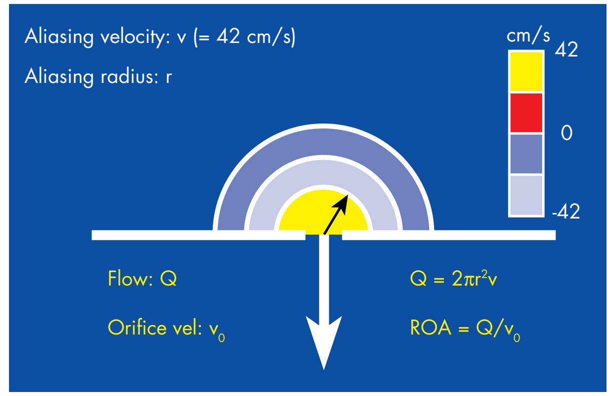

Figure 3 The proximal convergence method. By using the aliasing velocity of the colour Doppler display, it is possible to measure the radius to an isovelocity shell as blood converges on the regurgitant orifice. Assuming a hemispheric shape to the shell, flow rate is given as $Q = 2\pi r^2 v$. Dividing this flow rate by the maximal velocity through the orifice (given by continuous wave Doppler) yields an estimation for the regurgitant orifice area (ROA).

Such an approach, unfortunately, is only available on one manufacturer's instrument at the current time.

While these volumetric methods are theoretically sound and have been well validated in many carefully performed trials, they have not achieved widespread use within the clinical echocardiographic community for a variety of reasons. First, they are time consuming to implement, requiring multiple measurements from a variety of echocardiographic imaging windows and multistage calculations. Furthermore, they are exquisitely sensitive to the error in the primary measurements, and an error in any of these will be propagated throughout all the calculations. This is compounded by the need to subtract two fairly large numbers from each other to obtain a much smaller number at the end of the process. The absolute value of the uncertainty in the measurement rises as the square root of the sum of the squares of the component uncertainties, but the relative uncertainty rises even more, since the denominator (the regurgitant volume) is so much smaller. For example, if we assume that mitral and aortic stroke volume can be measured with approximately 15% accuracy (not a bad accuracy), we might obtain the following sample calculations: aortic stroke volume, 70 (10) ml; mitral stroke volume, 100 (15) ml; mitral regurgitant volume, 30 (18) ml, indicating that the 95% confidence intervals for regurgitant volume (2 standard deviations) extend from –6 ml to 66 ml, a range which is simply too great to be clinically useful. For these reasons, echocardiographic clinicians have turned with great enthusiasm to more direct methods, in particular the proximal convergence method.

Proximal convergence method

The proximal convergence method is a more direct approach to the quantification of valvar regurgitation. As blood rushes into a regurgitant orifice, it forms concentric shells of increasing blood velocity and decreasing surface area. Since blood is incompressible, if we could measure flow through any one of the shells, that would yield the instantaneous flow through the regurgitant orifice itself.[8] Fortunately, there is a straightforward way to estimate flow through one of the shells. Fluid dynamics theory demonstrates that for a small orifice in a flat plate, these isovelocity shells are hemispheric in shape, with an area of $2\pi r^2$, where r is the distance of the shell from the regurgitant orifice. Multiplying this area by the velocity v of the isovelocity shell will yield the flow rate. This radius and velocity can most easily be obtained by using the aliasing of the colour Doppler display, as blood rushes into the orifice. As shown schematically in fig 3, as blood velocity increases, there is an abrupt change from yellow to blue at which point we know the blood is moving at 42 cm/s and where we can easily measure the radius from the regurgitant orifice. Once flow rate is obtained as $Q = 2\pi r^2 v$, then the regurgitant orifice area (ROA) is obtained by dividing this by the maximal velocity through the valve measured with continuous wave Doppler: ROA = Q/v_{max}. This approach has been well validated in a number of experimental and clinical studies.[9] It has advantages over the volumetric approach in that all measurements are obtained from a single imaging window, typically one of the apical windows, and the flow rate is measured directly, not requiring subtraction of two large quantities from each other as in the volumetric approach. Nevertheless, there are some limitations to the proximal convergence method, also known as the PISA (proximal isovelocity surface area) method, which the reader should be aware of. Additionally, there is an important simplification to this method that will greatly aid in its clinical application.

Limitations to the proximal convergence method

There are four important limitations to the proximal convergence method: flattening of the contours near the orifice, constraint of the flow by proximal structures, uncertainty in localising the regurgitant orifice, and variability in the regurgitant orifice throughout cardiac cycle. These will be dealt with in turn.

Contour flattening of the orifice

Since the regurgitant orifice is in fact not infinitely small, the hemispheric shape of the isovelocity contours is not maintained all the way into the orifice; rather, they flatten out on approach to the orifice, and if flow were calculated using the standard formula, flow underestimation would ensue. An in vitro and computational study has shown that this underestimation is closely related to the aliasing velocity used in calculating the flow rate.[10] For example, if an aliasing velocity (v_a) that is 10% of the orifice velocity is used, then approximately 10% of the flow will be missed with the standard formula. This underestimation can be corrected by multiplying the calculated flow rate by the quantity $v_{max}/(v_{max} - v_a)$. Fortunately, for

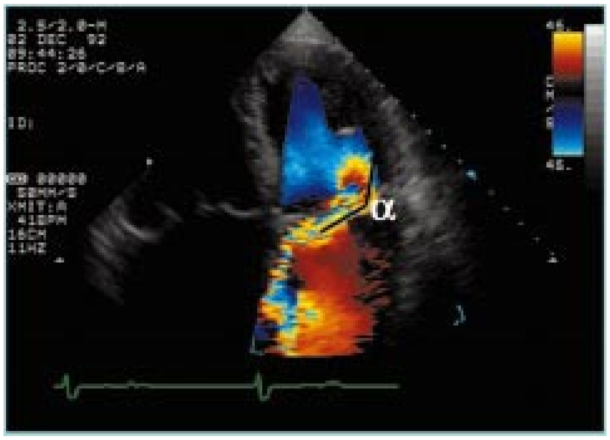

Figure 4 The influence of proximal flow constraint. In this patient with a flail posterior leaflet, the proximal convergence zone is constrained by the posterolateral wall, pushing the contours outward. This can be corrected by calculating flow rate in the usual manner and then multiplying by α/180.

left sided lesions (aortic and mitral regurgitation), this correction factor is rarely needed, since the aliasing velocity usually is less than 10% of the orifice velocity. The correction may be necessary for tricuspid regurgitation, where the aliasing velocity is a larger proportion of the orifice velocity and the underestimation of flow would be more significant.

Flow constraint by proximal structures

A more important limitation is the distortion in the isovelocity contours caused by encroachment of proximal structures on the flow field. For example, fig 4 shows mitral regurgitation caused by a flail posterior leaflet, where the convergence zone is immediately adjacent to the posterolateral wall. It is clear that the proximal convergence zone cannot form full hemispheric contours, and thus is pushed outward from the orifice. Applying the standard formula in this case would lead to significant flow overestimation, but again a simple solution to this exists. By simply excluding from the calculations an amount of flow approximately equal to the geometric reduction in the orifice shape from a hemisphere, most of this overestimation can be eliminated.[11] Ideally, a full three dimensional analysis of the flow field would allow refinement of the method, but until such methods are widely available, the simple "eyeball" approach works reasonably well. As shown in fig 4, simply multiplying the calculated flow rate by the ratio α/180 will permit estimation of the true flow rate.

Where's the orifice?

While it is generally quite easy to see where the colour Doppler display changes from blue to red, it is often not so easy to see exactly where the centre of the regurgitant orifice is located. This is an important issue, as the radius is defined on the basis of that orifice location; and since the radius is squared in the proximal convergence formula, a 10% error in radius measurement will cause more than 20% error in flow rate and regurgitant orifice area calculations. When the images are being obtained live on the echo machine, it is possible to freeze the image and toggle colour display on and off, improving the anatomical delineation of the regurgitant orifice. Once the images are stored off either digitally or on videotape, however, the colour generally is a fixed overlay on the black and white anatomy and cannot be removed. While some automated methods have been proposed to localise the orifice automatically from the full velocity field,[12] these have not reached clinical use yet. Another alternative is to look not at the first aliasing radius but rather to look at the separation between the first

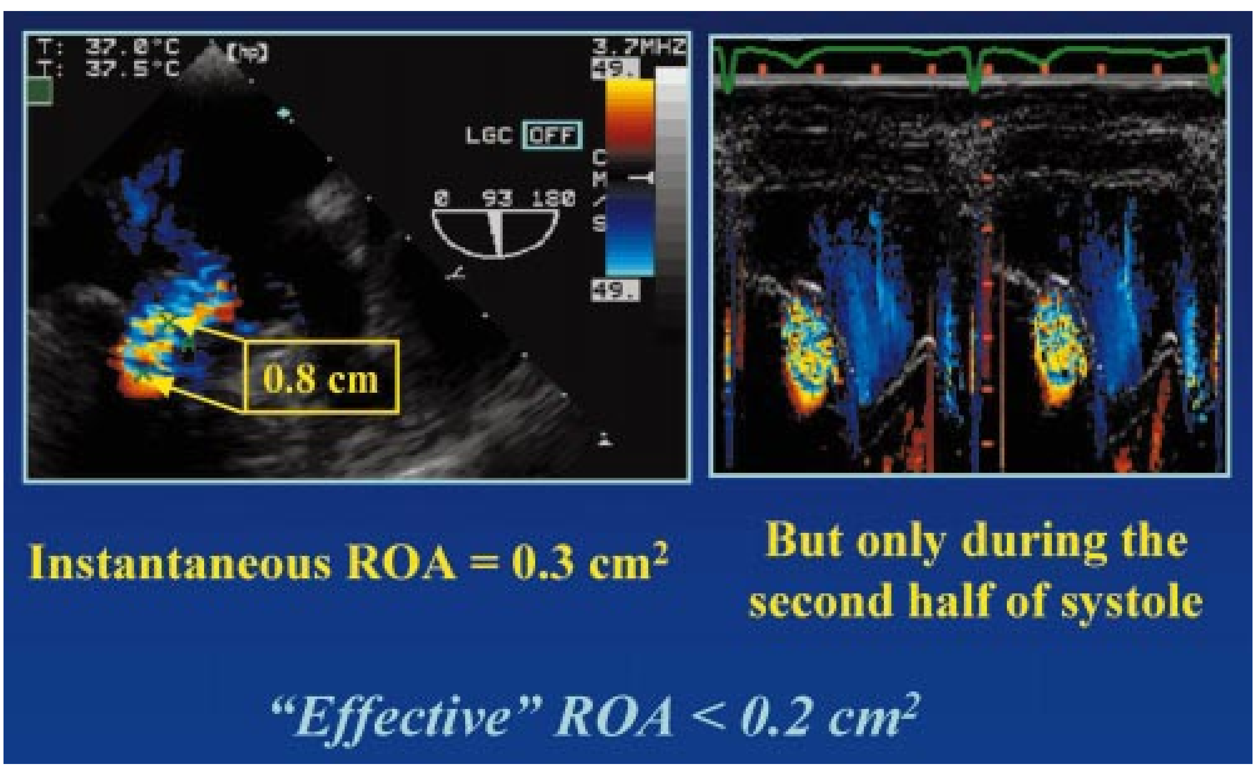

Figure 5 Variability of the regurgitant orifice area throughout the cardiac cycle. In this patient with mitral valve prolapse, there is a large regurgitant orifice area at peak regurgitation (0.3 cm^2), but as shown on the colour M mode to the right, this significant regurgitation only occurs in the latter half of systole, so that the effective regurgitant orifice area is less than 0.2 cm^2.

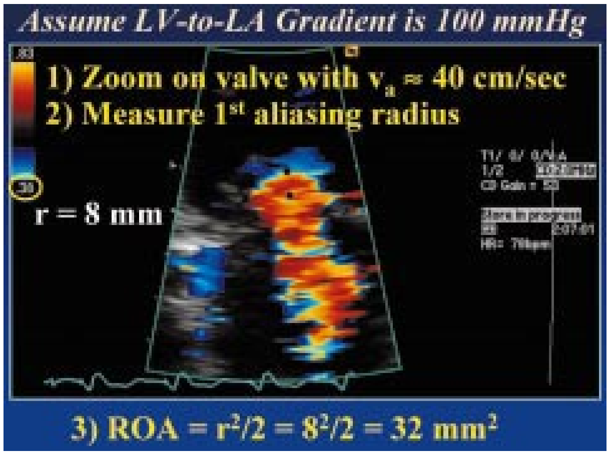

Figure 6 Simplification of the proximal convergence method. By assuming that the left ventricle (LV) to left atrium (LA) pressure difference is 100 mm Hg and setting the aliasing velocity to approximately 40 cm/s, the regurgitant orifice area can be calculated simply as ROA = $r^2/2$.

and second aliasing contours.[13] Clinical experience with this interaliasing distance method is limited, but it may prove helpful, particularly for moderate to severe mitral regurgitation where a second aliasing contour is visible.

Variable regurgitant orifice

In many patients the degree of regurgitation is not constant throughout systole (or diastole in the case of aortic regurgitation), and categorising the regurgitant severity on the basis of the maximal regurgitant orifice area may give a misleading overestimation of the haemodynamic impact of the regurgitation. For example, in cases of classic mitral valve prolapse, the severe regurgitation is often confined to the latter half of systole. Conversely, it has been shown in some cases of functional mitral regurgitation in dilated cardiomyopathy that the most significant regurgitation occurs early in systole and then again during isovolumic relaxation with relatively little flow in mid systole, as ventricular pressure is sufficient to keep the valve closed.[14] One way of addressing this issue is to image the proximal convergence zone with colour Doppler M mode echocardiography, which shows a temporal display of the velocity through the valve throughout cardiac cycle. Figure 5 shows a patient with mitral valve prolapse in whom significant regurgitation occurs only at the end of systole. While methods have been proposed for using the colour M mode display in a quantitative fashion,[15] it is often possible to use it in a semiquantitative fashion simply to adjust the clinical judgment of the severity of regurgitation based on the duration of the leakage.

Simplified proximal convergence method

While the proximal convergence method is considerably simpler then the previous volumetric methods, it is still considered by some to be too complex for routine clinical application. To address this issue, we have devised a simplification to the proximal convergence method that allows the mitral regurgitant orifice area to be estimated with only one measurement.[16] Underlying this simplification is an assumption that the driving pressure between the left ventricle and the left atrium is 100 mm Hg (which would yield a 5 m/s mitral regurgitant jet). With this assumption, if the aliasing velocity is set to approximately 40 cm/s and the radius of the first aliasing contour obtained, then the regurgitant orifice area is stated quite simply as: ROA = $r^2/2$. Figure 6 shows an application of this method in a patient with moderately severe mitral regurgitation from an inferoposterior infarction. After zooming on the proximal convergence zone and baseline shifting to an aliasing velocity of 38 cm/s (close enough to 40 for this application), the aliasing contour is noted 8 mm from the regurgitant orifice, yielding a regurgitant orifice area of 32 mm². A recent validation study has shown that this simplified method yields results that are almost the same as the more complete proximal convergence method. Naturally, to the extent that the left ventricle to left atrium pressure difference differs from 100 mm Hg, there will be some intrinsic error in the calculations, but over a pressure range between 64–144 mm Hg, this error should not exceed 20% or 25%. Using the simplified method, it is possible to add quantitation to the assessment of mitral regurgitation with only a minute or two of extra imaging and calculation.

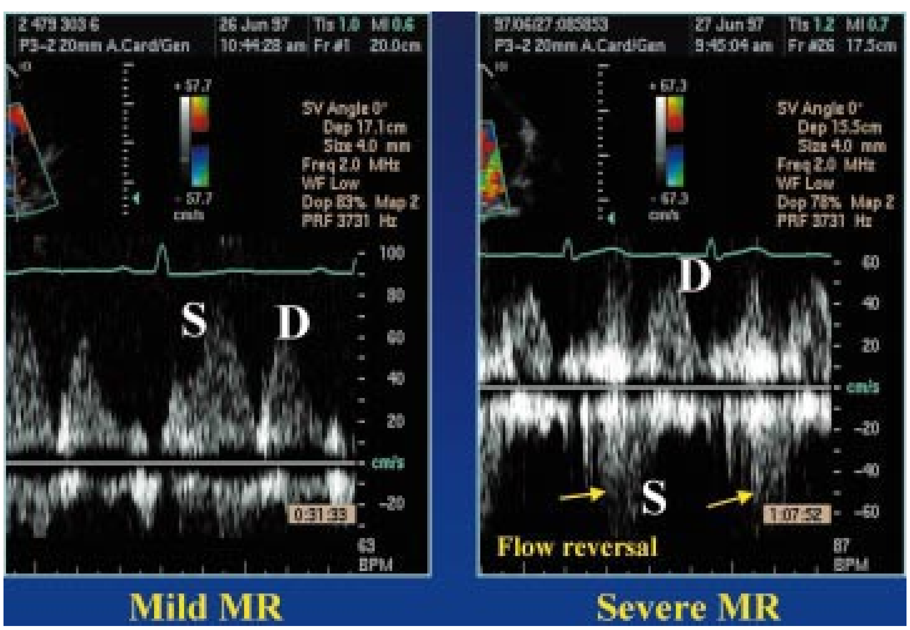

Figure 7 Impact of mitral regurgitation on pulmonary venous flow. With mild mitral regurgitation the pulmonary venous S wave is larger than the D wave (left panel), while with severe mitral regurgitation the S wave becomes frankly reversed.

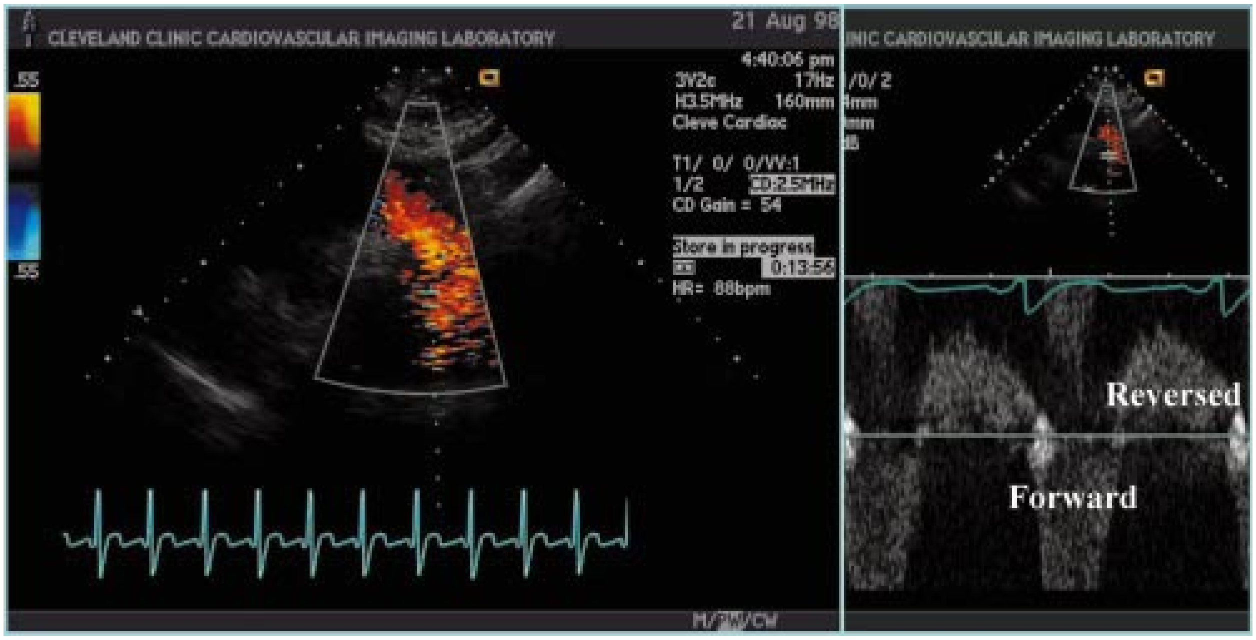

Figure 8 Aortic flow reversal indicates haemodynamically significant aortic regurgitation. By positioning a pulsed Doppler sample volume in the distal aortic arch (left panel), the ratio of the forward versus reversed velocity time integrals gives a rough estimate of the regurgitant fraction (right panel).

Vena contracta method
Another direct approach to quantifying the regurgitant orifice area is by direct visualisation of the vena contracta, the narrowest portion of the regurgitant jet just behind the leaking valve. This has long had a role in the assessment of aortic regurgitation[17] and has recently been proposed for mitral regurgitation.[18] While this approach is theoretically sound, it is limited by the lateral resolution of colour Doppler echocardiography, which frequently is inadequate to distinguish minor variations in the width of the vena contracta.

METHOD SPECIFIC TO INDIVIDUAL VALVES
In addition to these general quantitative and colour jet area techniques, there are several parameters that are useful for only the mitral or aortic valve.

Mitral valve
Assessment of pulmonary venous flow is a useful adjunct in the characterisation of mitral regurgitation.[19] Normally the S wave (during ventricular systole) is larger than the D wave. With progressive degrees of mitral regurgitation, however, the maximal velocity of the S wave is reduced, becoming frankly reversed when mitral regurgitation is severe. Figure 7 shows an example of normal versus reversed pulmonary venous flow. Unfortunately, the intermediate pattern, where the S wave is merely blunted (smaller than the D wave but not reversed) is very non-specific. It may be an indicator of moderately severe mitral regurgitation, but it also occurs in situations of left ventricular dysfunction and atrial fibrillation.[20] Another useful adjunct in assessing mitral regurgitant severity is inspection of the transmitral flow pattern. It is almost impossible to have haemodynamically significant mitral regurgitation without having an elevated E wave through the mitral valve.

Aortic valve
For the aortic valve there are two special indices that are useful in characterising regurgitation: the aortic pressure half-time, and flow reversal in the aorta. The aortic pressure half-time is obtained from the continuous wave Doppler recording of reversed flow across the aortic valve in diastole.[21] By measuring the time required for the aorta-to-left ventricle pressure difference to fall by half, one gets an indication of the severity of regurgitation, with values less than 250 ms typically indicating haemodynamically significant regurgitation. However, the pressure half-time depends critically on the chronicity of the regurgitation, with acute aortic regurgitation leading to much shorter values than longstanding leakage, in which case the ventricle has dilated with increased compliance. In addition, the half-time also varies with systemic vascular resistance, such that patients who are treated with vasodilators may shorten their half-time even as the aortic regurgitant fraction improves, in contrast to the usual expectation of this parameter.[22]

When aortic regurgitation is haemodynamically significant, flow reversal may be visualised in the aortic arch and descending aorta.[23] As shown in fig 8, the ratio of the reversed flow to the forward flow velocity time integral may be taken as an estimate of the aortic regurgitant fraction. Indeed, if I were to be given only one piece of data upon which to decide whether aortic regurgitation was haemodynamically significant or not, a pulsed Doppler recording in the distal aortic arch would probably be the best one.

CONCLUSIONS
Careful quantification of valvar regurgitation is critical for deciding on the need and success of medical management as well as determining the timing of surgery. The colour Doppler jet area method, despite its many limitations, is still useful for separating regurgitation into several broad degrees of severity. However, any patient with a significant degree of regurgitation should undergo a formal quantification study, which in general can most easily and accurately be done using the proximal convergence method. Combining this with observations of chamber size and function, pulmonary artery pressure, and adjunct parameters such as pulmonary venous flow and aortic flow, will

give the echocardiographer much improved confidence in the proper assessment about the regurgitation.

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