CARDIOVASCULAR MEDICINE

Automated quantification of aortic regurgitant volume and regurgitant fraction using the digital colour Doppler velocity profile integration method in patients with aortic regurgitation

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Background: The recently introduced automated cardiac flow measurement (ACM) technique provides a quick and an accurate automated calculation of stroke volume and cardiac output. This is obtained by spatio-temporal integration of digital Doppler velocity profile data.

Objective: To evaluate the use of the ACM method in the non-invasive assessment of aortic regurgitant volume and per cent regurgitant fraction (%RF) in patients with aortic regurgitation.

Methods: Aortic outflow volume and mitral inflow volume were calculated by the ACM method in 22 patients with isolated aortic regurgitation. Aortic regurgitant volume and %RF were calculated using the following equations: aortic regurgitant volume = [aortic outflow volume] - [mitral inflow volume]; %RF = [aortic regurgitant volume]/[aortic outflow volume] × 100. The results were compared with those obtained using pulsed Doppler cross sectional echocardiography (PD-2D).

Results: Aortic regurgitant volumes measured by the ACM method showed a good correlation with the PD-2D measurements ($r = 0.95$, $y = 0.9x + 3.9$, $SEE = 8.6$ ml); the mean (SD) difference between the two methods was -1.5 (8.5) ml. %RF estimated by the ACM method also correlated well with the values obtained by the PD-2D method ($r = 0.91$, $y = 0.9x + 4.9$, $SEE = 6.0\%$); the mean difference between the two methods was -1.5 (6.0)%. Total time required for aortic regurgitant volume (for one cardiac cycle) by the ACM method was significantly shorter than by the PD-2D method (130 (16) v 230 (32) s, $p < 0.01$).

Conclusions: The newly developed the ACM method is quick and accurate in the automated assessment of aortic regurgitant volume and per cent regurgitant fraction in patients with isolated aortic regurgitation.

In patients with aortic regurgitation, accurate evaluation of the severity of the regurgitation is important in determining whether surgical correction is required. Colour Doppler visualisation of aortic regurgitant jets has been used clinically for this purpose.¹⁻³ However, the area and length of the regurgitant jet depends not only on the regurgitant volume and flow rate but also on the flow velocity (pressure difference), chamber compliance, and wall constraint.^{6,7} Because of this, several different methods have been applied to quantify the severity of aortic regurgitation by measuring the regurgitant volume or regurgitant fraction (RF) using Doppler echocardiography.⁸⁻¹⁵

Recently a new quantitative technique which uses spatio-temporal integration of digital colour Doppler velocity profile data¹⁶⁻¹⁸ has been developed for automated cardiac flow measurement (ACM). This method provides quick and accurate automated calculation of stroke volume and cardiac output. Recent studies have shown that it yields regurgitant volume and regurgitant fraction measurements that are equivalent to standard pulsed Doppler cross sectional echocardiography (PD-2D) in patients with mitral regurgitation.^{19,20} To our knowledge, however, the only report of the use of ACM in the evaluation of aortic regurgitation was one animal study.²¹ We therefore applied the ACM technique to patients with significant isolated aortic regurgitation to compare the ACM and the PD-2D methods for determining aortic regurgitant volume and regurgitant fraction.

METHODS

Study patients

Patients were included prospectively and examined in the echocardiographic laboratory. Inclusion criteria were, first, pure isolated aortic regurgitation of more than the most mild degree, as determined by standard cross sectional Doppler colour flow imaging, and second, normal sinus rhythm. Of the 26 patients who met these criteria, four were excluded because of difficulty in obtaining complete cross sectional images or because pulsed Doppler and colour Doppler image quality was inadequate. Thus 22 patients were included in the study (12 male, 10 female; mean age 61 years; range 30-84 years).

The aetiology of the aortic regurgitation included rheumatic disease (7), bicuspid aortic valve (4), annular dilatation (4), calcification (3), and unknown (4).

PD-2D echocardiographic analysis

Quantitative Doppler measurements and calculations were done at the time of the examination using an ultrasound imaging system with a 2.5 MHz transducer (Toshiba SSA-380A, Power Vision, Tochigi, Japan). The aortic outflow and mitral inflow volumes were calculated using the product of the pulsed Doppler time-velocity integral and the area of the

Abbreviations: ACM, automated cardiac flow measurement; PD-2D, pulsed Doppler cross sectional echocardiography; RF, regurgitant fraction

Figure 1 (A) An example of measurement of aortic outflow volume in the long axis view by the automated cardiac flow measurement (ACM) method. Region of interest set on the aortic annulus on the display to obtain the velocity profile. Flow volume rate is obtained by spatial integration of the velocity profile throughout the systolic period. (B) An example of measurement of mitral inflow volume in the two chamber and four chamber views by the ACM method. Flow volume is measured by the temporal integration of the flow volume rate obtained by spatial profile integration of the velocity profile throughout the diastolic period. LA, left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle.

annuli of the aortic and mitral valves, as described previously.^{8-9,22} The diameter of the annulus in systole was measured at the point of insertion of the leaflets. The diameter of the mitral annulus was measured at the time of maximum valvar opening from both four and two chamber views. Assuming an elliptic shape, we calculated the cross sectional annular area as πab , where "a" and "b" are halved diameters of the annulus in the four and two chamber views.^{23,24} The apical approach was used to record the pulsed wave Doppler signal at the aortic and mitral annuli, and integrals were obtained by manually tracing the Doppler spectrum. We traced the modal velocity of both the mitral inflow and the aortic outflow from the pulsed Doppler waveform. The average from the three measurements of each variable was recorded. The aortic regurgitant volume and per cent regurgitant fraction (%RF) were calculated as follows:

$$\text{Aortic regurgitant volume} = [\text{aortic outflow volume}] - [\text{mitral inflow volume}]$$

$$\%RF = [\text{aortic regurgitant volume}] / [\text{aortic outflow volume}] \times 100$$

ACM method

The principle of the ACM method has been described previously.¹⁶⁻²¹ Colour Doppler echocardiography was undertaken with a Toshiba SSA-380A ultrasound imaging system equipped with prototype ACM software and a 2.5 MHz transducer. Frame rate was set at 27 frames/s with a 30° colour sector. The pulse repetition frequency was 4.5 kHz. The aliasing phenomenon was prevented by shifting the colour baseline (Doppler zero shift) velocity up to approximately 1.4 m/s. The cut off frequency of the wall filter was set high enough to eliminate the clutter signals from the moving tissue (cut off frequency 900 Hz). An optimal gain setting was obtained without random colour noise in the non-flow areas by maximising the gain level.

ACM was done immediately after PD-2D by a single examiner who did not know the results of the PD-2D study. Colour Doppler image acquisition was obtained from the apical-long axis view for aortic outflow measurements (fig 1A). Several beats of colour images were recorded sequentially on the image memory. On the selected beat, the systolic period was manually defined by a trigger mark based on the ECG. A region of interest was set on the aortic annulus in the display to obtain the velocity profile. For each frame of the colour images, flow volume rate was calculated by rotational integration of the velocity profile in the region of interest. Stroke volume was measured by the temporal integration of the flow volume rate throughout the systolic period. Three measure-

ments of each variable were averaged to determine aortic outflow volume.

For mitral inflow volume measurements, colour Doppler image acquisition was obtained from both apical four chamber and two chamber views (fig 1B). Several beats of colour images were recorded sequentially on the image memory. A region of interest was set on the mitral annulus in the display to obtain the velocity profile. Flow volume was measured throughout the diastolic period by the temporal and spatial integration of measured velocity profile. Three measurements of each variable were averaged to determine flow volume in both four and two chamber views separately. Final mitral inflow volume was determined by averaging flow volume from the two views.

Statistical analysis

Linear regression analysis was used to compare the PD-2D and the ACM assessment of aortic regurgitant volume and regurgitant fraction. Differences in the measurements by each method were expressed as mean (SD). Analyses of the differences in the measurements were done using the technique of Bland and Altman.²⁵

We measured the time required to calculate aortic regurgitant volume in one cardiac cycle by both the ACM and the PD-2D method. For the ACM method, the measured time values included optimising the image, selecting the systolic and diastolic periods from the stored image memory, positioning a desired region of interest, and performing the automated integration of aortic outflow and mitral inflow in one recorded cardiac cycle. For the PD-2D method, the measured time values involved optimisation of the image, tracing the Doppler spectrum of aortic outflow and mitral inflow, and measuring the diameter of the aortic and mitral annuli. We used the paired *t* test to compare the time required for aortic regurgitant volume calculation by the ACM method with that by the PD-2D method. A probability value of *p* < 0.01 was considered significant.

RESULTS

Aortic regurgitant volume

Aortic regurgitant volume measurement by the ACM method showed a good correlation with the PD-2D measurement ($r = 0.95$, $y = 0.91x + 3.9$, SEE = 8.6 ml) (fig 2, left). The mean difference between the PD-2D and ACM methods was -1.5 (8.5) ml (fig 2, right).

Per cent regurgitant fraction

Regurgitant fraction estimated by the ACM method correlated well the PD-2D estimation ($r = 0.91$, $y = 0.90x + 4.9$, SEE = 6.0%) (fig 3, left). The mean difference between the PD-2D and the ACM methods was -1.5 (6.0)% (fig 3, right).

Figure 2 Left panel: scatterplots showing correlation between automated cardiac flow measurement (ACM) and pulsed Doppler-cross sectional (PD-2D) echocardiographic measurement of aortic regurgitation. Right panel: scatterplots showing mean aortic regurgitant volume by the ACM and PD-2D methods (x axis) and the difference between ACM and PD-2D measurements (y axis). The mean difference and 2 SD limits are shown.

Figure 3 Left panel: scatterplots showing correlation between automated cardiac flow measurement (ACM) and pulsed Doppler-cross sectional (PD-2D) echocardiographic measurement of regurgitant fraction. Right panel: scatterplots showing mean regurgitant fraction by the ACM and PD-2D methods (x axis) and the difference between ACM and PD-2D measurements (y axis). The mean difference and 2 SD limits are shown.

Time required for aortic regurgitant volume calculation

The time required for aortic regurgitant volume calculation in one cardiac cycle by the ACM method was significantly shorter than by the PD-2D method (130 (16) v 230 (32) seconds, $p < 0.01$).

DISCUSSION

In this study, we showed that aortic regurgitant volume and regurgitant fraction assessed by the ACM method were closely correlated with the values obtained using the conventional PD-2D method. The time required for aortic regurgitant volume calculation by the ACM method was significantly shorter than by the PD-2D method. These results suggested that the ACM method would be clinically useful in the quantitative assessment of aortic regurgitant volume and regurgitant fraction in patients with isolated aortic regurgitation.

Previous studies

Several echocardiographic techniques for evaluating aortic regurgitation have been used in the clinical setting. Previous studies have suggested that colour Doppler flow mapping is of value in detecting regurgitant flow in real time, and it provides an initial estimate of the severity of the regurgitation by measuring the area or length of the regurgitant jet.¹⁻⁵ However, the technique depends not only on regurgitant volume and flow rate but also on flow velocity (pressure difference), chamber compliance, and wall constraint.⁶⁻⁷ In order to quantify the severity of aortic regurgitation, the PD-2D method has been employed, as this measures the flow velocity integral of the aortic outflow volume and mitral inflow volume.^{8-9 22 23} Although this method is reported to be accurate for evaluating the severity of isolated aortic regurgitation, the processes of calculating the flow volume are tedious and time consuming. Recently, colour Doppler flow mapping of a proximal isovelocity surface, which corresponds to a blue-red interface orifice,

has drawn attention to the possibilities of quantifying valvular regurgitation, especially in patients with mitral and tricuspid regurgitation. Under clinical conditions, however, the success rate of acquiring a proximal isovelocity surface for aortic regurgitation is significantly less than for mitral regurgitation.¹³⁻¹⁵ This is because of several specific limitations to obtaining the aortic proximal isovelocity surface, such as the Doppler angle and thickened valvular tissue, which do not pose a problem with mitral or tricuspid regurgitation.^{14 15}

The ACM method

The ACM method that was applied in the present clinical study was developed for the automated measurement of flow volume using the spatial and temporal integration of the Doppler velocity profile.¹⁶⁻²¹ Recent reports have shown that there are good correlations between ACM and thermodilution or PD-2D echocardiographic methods for estimating cardiac output in experimental clinical studies.¹⁶⁻¹⁸ There are also reports of the validity of quantifying regurgitant volume and regurgitant fraction in patients with isolated mitral regurgitation using the ACM method.^{19 20} To our knowledge, this is the first report to evaluate the severity of aortic regurgitation using the ACM method in the clinical setting.

We found several advantages to using the ACM method. First, we could calculate the flow volume rate without tracking the Doppler waveform. Second, we did not need to measure the area of the flow tract. Finally, we needed only two manual procedures—the selection of systolic and diastolic periods in the stored image memory, and the positioning of a region of interest on the mitral and aortic annulus in the Doppler colour flow image. These advantages meant that calculation of flow volume was simpler and quicker than with the PD-2D method. Thus this new technique shortens the examination time for measuring aortic regurgitant volume and regurgitant fraction, and can easily be applied to quantifying aortic regurgitation in the clinical setting.

Previous studies have shown a good correlation between regurgitant fraction derived by the PD-2D method and by invasive methods, while the correlations involving absolute measures of aortic regurgitant volume have not been so good.¹⁰ Our study, however, showed an excellent correlation between the PD-2D and ACM methods for determining both regurgitant fraction and aortic regurgitant volume. Perhaps this relates to improvements in instrument technology for Doppler echocardiography.

Study limitations

Our study had some limitations. First, we compared ACM with the PD-2D method for evaluating the severity of aortic regurgitant volume and regurgitant fraction. Although the PD-2D method has been accepted in the clinical setting, there may be circumstances where it is not ideal.^{8-9,22} However, there is no true gold standard against which to test the new method in clinical studies. Second, we did not attempt to measure the aortic regurgitant volume directly in the present study. In the animal setting, a previous study has reported that aortic regurgitant volume could be determined by measuring aortic regurgitant flow directly in ascending aorta from the apical long axis view.²¹ In the clinical setting, however, it was difficult to obtain a good colour Doppler flow image of ascending aortic flow using a conventional approach. Finally, we did not evaluate the correlation between aortic regurgitation quantified by the ACM method and by other methods such as jet width, jet height, and angiography. However, the purpose of our study was specifically to compare aortic regurgitant volume and regurgitant fraction determined by the ACM method with the values obtained by the PD-2D method, which is already established as a quantitative technique.

Conclusions

We showed that the newly developed ACM method is rapid and accurate for the automated assessment of aortic regurgitant volume and per cent regurgitant fraction in patients with isolated aortic regurgitation.

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