Blood Flow Velocity Profiles in the Aortic Annulus: A 3-Dimensional Freehand Color Flow Doppler Imaging Study

Bjørn Olav Haugen, MD, Sevald Berg, PhD, Kjell Morten Brecke, MSc, Hans Torp, Dr Techn, Stig Arild Slørdahl, MD, PhD, Terje Skjærpe, MD, PhD, and Stein Olav Samstad, MD, PhD, *Trondheim, Norway*

Background: **The use of a single sample volume in Doppler measurements of the velocity time integral (VTI) in the aortic annulus may introduce errors in calculations of stroke volumes, shunts, regurgitant fractions, and aortic valve area. To study the blood flow velocity distribution and assess this potential error, we used a dynamic 3-dimensional color flow Doppler imaging method.**

Methods and Results: **Seventeen healthy volunteers were studied. The ultrasound data were captured from 10 to 20 heartbeats at a high frame rate (mean 57 frames per second) while freely tilting the transducer in the apical position. A magnetic position-sensor system recorded the spatial position and orientation of the probe. The raw digital ultrasound data were analyzed off-line with no loss of temporal resolution. Blood flow velocities were integrated across a spherical surface that tracked the aortic annulus during systole. The ratios of the systolic maximum to the systolic mean VTI ranged from 1.2 to 1.5 (mean 1.4). At the time of systolic peak flow, the ratios of the maximum to the mean velocity ranged from 1.1 to 2.0 (mean 1.5). The location of the maximum velocities and VTI showed individual variation.**

Conclusion: **The blood flow velocity profile was nonuniform. By using a single sample volume in Doppler measurements of the VTI in the aortic annulus, errors ranging from 20% to 50% may be introduced in calculations of stroke volumes.** (J Am Soc Echocardiogr 2002;15:328-33.)

Knowledge of the velocity distribution in the aortic annulus is of importance to the clinician for several reasons: The pulsed wave (PW) Doppler technique in measurement of stroke volumes assumes a flat profile.[1] Errors can be introduced as the sampled velocities over- or underestimate the mean velocity time integral (VTI). The technique is applied to measurements of stroke volumes in the left ventricular outflow tract (LVOT), the pulmonal artery, and the mitral orifice and will affect calculations of shunts[2] and regurgitant fractions[3,4] as well. Further, any error in measurement of velocities in the LVOT will influence calculations of the aortic valve area in aortic stenosis when using the equation of continuity.[5]

Invasive techniques, such as perivascular PW ultrasound Doppler,[6] intraluminal PW ultrasound Doppler,[7,8] and hot-film anometry,[9] as well as magnetic resonance imaging (MRI)[10-12] have been used in studies of velocity profiles in the ascending aorta. Noninvasive ultrasound[13-16] and MRI[17] have been used in studies of the velocity profile in the LVOT and the aortic annulus and have shown that the profile in the distal LVOT and the aortic annulus is skewed, with the highest velocities located toward the septum. However, the color flow Doppler studies were limited by recordings from only 1 or 2 planes. Further, blood flow measured by Doppler gives velocities relative to the direction of the ultrasound beam propagation. To get correct velocity values, representing the flow through the valve, the movement of the annulus should be taken into account. Similarly, low temporal resolution, a fixed level of measurement, and long acquisition time were limitations to the MRI study.[17] We wanted to apply a freehand 3-dimensional (3D) color flow Doppler imag-

From the Departments of Cardiology and Lung Medicine, and Physiology and Biomedical Engineering (S.B., K.M.B., H.T., S.A.S., S.O.S.), Norwegian University of Science and Technology, Trondheim, Norway.

Supported by grants from the Norwegian Council on Cardiovascular Diseases.

Reprint requests: Bjørn Olav Haugen, MD, Department of Cardiology, University Hospital of Trondheim, Olav Kyrres gt 17, N-7006 Trondheim, Norway (E-mail: *Bjorn.O.Haugen@medisin.ntnu.no*).

Copyright 2002 by the American Society of Echocardiography.

0894-7317/2002/$35.00 + 0 **27/1/117292**
doi:10.1067/mje.2002.117292

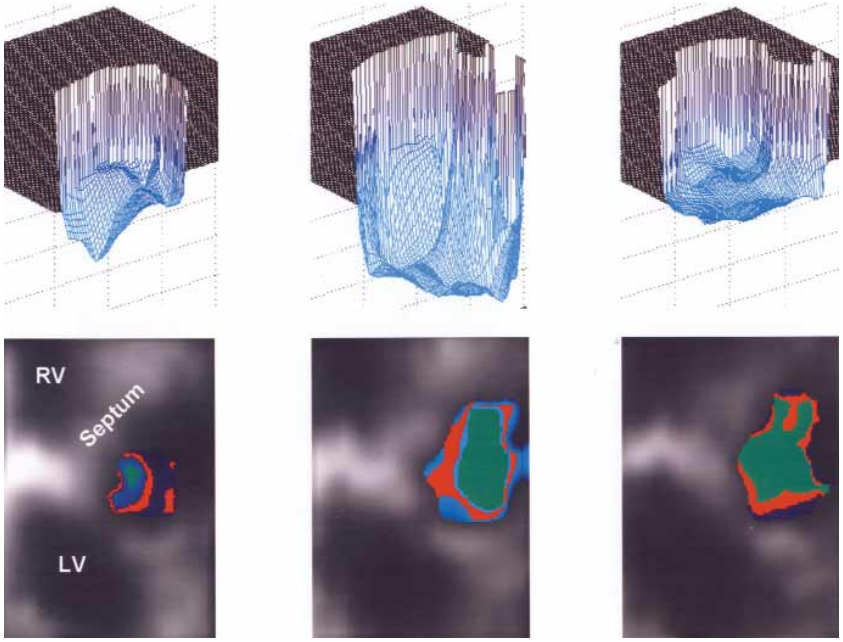

Figure 1 Examples of 3-dimensional velocity profiles from early systole, peak flow, and late systole. Profiles are visualized as mesh plot and encoded as color flow Doppler in 2-dimensional slices extracted from 3-dimensional data. Height of mesh plot is proportional to blood flow velocities. Corresponding 2-dimensional slice is located below each mesh. *Green*, Maximum velocity; *Red*, mean velocity; *LV*, left ventricle; *RV*, right ventricle.

ing method,[18,19] using digital raw ultrasound data acquired at a high frame rate to assess the blood flow velocity distribution in the aortic annulus. Blood flow velocities were measured through a spherical surface, which followed the movement of the aortic annulus during systole.

METHODS

Subjects

Twenty-four subjects, 16 men and 8 women, with no history of cardiac disease were included in the study. Mean age was 27.8 (range 19-48) years. All the recordings from all the subjects were acquired before the quality was evaluated off-line. Seven subjects were excluded. One was excluded because of an unstable electrocardiogram (ECG) and 6 because of poor 3D-image quality. All subjects had sinus rhythm. The regional committee on human research approved the study, which complied with the Declaration of Helsinki. All subjects gave informed consent to participate.

Equipment

A digital ultrasound scanner (System Five, GE Vingmed Ultrasound, Horten, Norway) with a 2.5-MHz phased-array transducer and a magnetic locating device (Flock of Birds, Ascension Technology Corp, Burlington, Vt) were used for data acquisition. The Flock of Birds tracked the spatial position and orientation of the transducer during the recording. Further processing was performed in an external, standard PC with a prototype version of the EchoPAC-3D software[20] (GE Vingmed Ultrasound, Horten, Norway) and MATLAB (MathWorks, Inc, Natick, Mass). This new 3D, high frame rate, color flow Doppler imaging technique has been described in detail in previous studies.[18,19,22]

Data Acquisition

The subjects were examined in the left lateral recumbent position. Each subject rested 15 minutes before blood flow velocities were recorded. The recordings were made in suspended end expiration to reduce cardiac movement while acquiring 3D data.

Recordings of tissue images were done in second harmonic imaging mode, with a transmit frequency of 1.7 MHz. In color flow Doppler imaging mode the center frequency of the transmitted pulse was 2.5 MHz.

A high frame rate was achieved by minimizing the tissue and color flow sector. In the 2-dimensional (2D) plane, at a depth of 10 cm, the sector size was about 3.3-cm wide in a typical recording. In the elevation direction, the size was dependent on the number of planes. We used 14 scanned beams in the azimuth direction to record flow velocities.

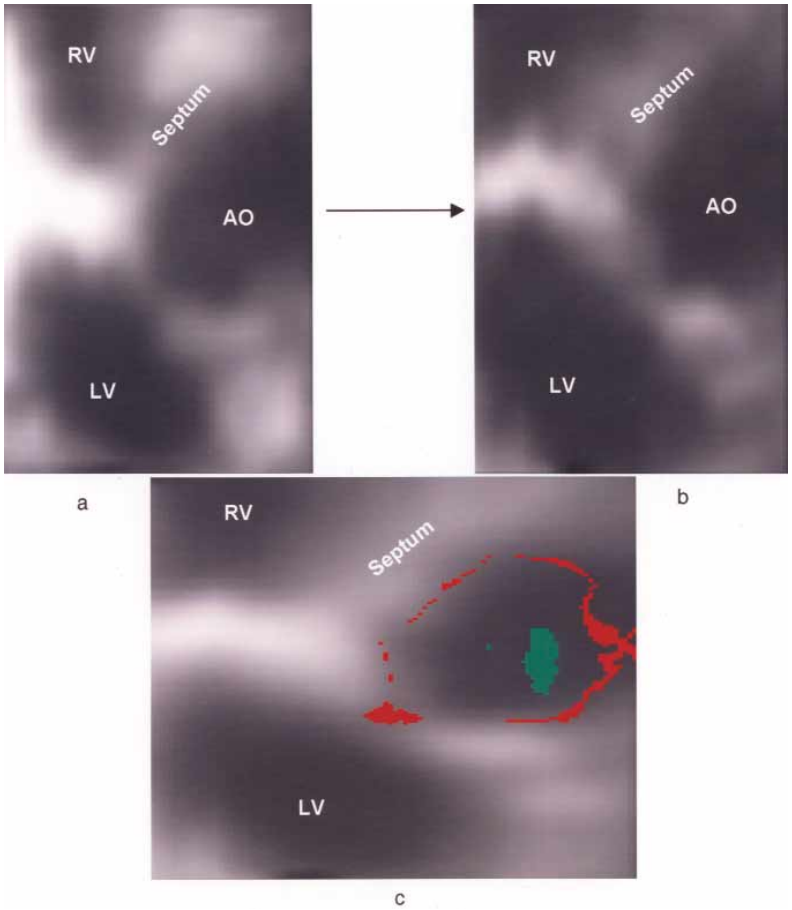

Figure 2 Example of location of mean (*red*) and max VTI (*green*) within the annulus (**c**). Tissue slices were averaged to constitute anatomical frame around mean and max VTI. Two tissue slices from early (**a**) and late systole (**b**) are shown to explain blurring of tissue in averaged slice (**c**). This was due to movement of anatomical structures during systole. *AO,* Aortic annulus; *LV,* left ventricle*; RV,* right ventricle; *VTI,* velocity time integral.

Mean frame rate in the 17 three-dimensional recordings was 57 frames per second (range 45-66).

The transducer was tilted from the posterior toward the anterior wall during 10 to 20 cardiac cycles. In this manner, the entire aortic annulus was intended to be covered. Each frame was stored with the corresponding position coordinates and the ECG signal in the digital replay memory of the ultrasound scanner.

Data Processing

Raw digital ultrasound data were transferred to a PC and analyzed off-line. Corresponding frames relative to the R-wave in the ECG were used to construct 3D volumes. In a 5-chamber view, the aortic valve was identified, and a spherical cross-sectional surface was positioned at the level of the septal part of the valve. This surface followed the movement of the aortic annulus throughout systole. In MATLAB, the blood flow velocities were calculated relative to the moving spherical surface, and true blood flow velocities through the annulus were obtained. Velocity vectors perpendicular to the surface, aligned with the ultrasound beam, were extracted from the 3D data and reconstructed in 2D slices as illustrated in Figure 1. The tissue and Doppler signals were filtered, and aliased blood flow velocities baseline shifted according to Berg et al.[19]

As a quantitative assessment of the velocity distribution, any possible skew was described by the ratio maximum VTI to the systolic mean VTI. The maximum velocity systolic peak flow was measured and compared with the mean velocity at the same time. Further, the locations of maximum velocity and mean velocities in each 2D slice were visualized as shown in Figure 1. Finally, the location of the maximum and mean VTI was visualized as shown in Figure 2, *C.*

RESULTS

The ratios of the maximum systolic to the mean VTI ranged from 1.2 to 1.5 (mean 1.4). At the time of sys-

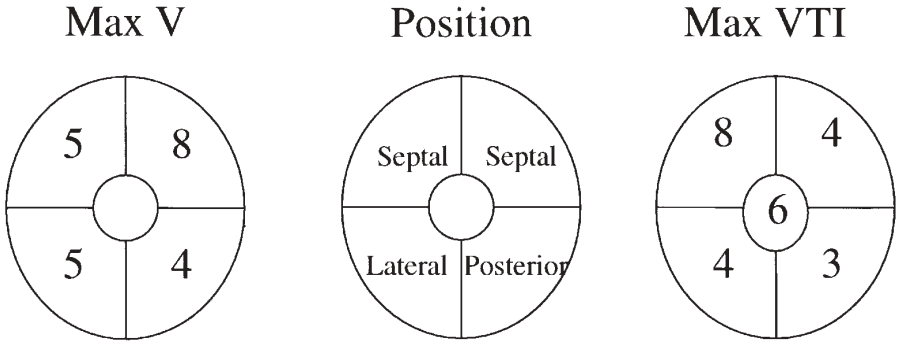

Figure 3 Appearance of maximum velocities (*Max V*) at peak flow and maximum velocity time integrals (*Max VTI*) in each of 5 areas in annulus was counted and summarized. N = 17.

tolic peak flow, the ratios of the maximum to the mean velocity ranged from 1.1 to 2.0 (mean 1.5).

The results are presented in Table 1. The mean VTI was located along the brim of the annulus, as illustrated in Figure 2, but the location of the maximum VTI was variable. The velocity profile is visualized as a mesh plot and as color flow Doppler in 2D slices extracted from the 3D data set. The location of the maximum velocity and the mean velocity, at the same time, was followed in each 2D slice throughout systole, as illustrated in Figure 1. The velocity profile was nonuniform and the location of the maximum velocity at peak flow and the maximum VTI showed variation (Figure 3).

DISCUSSION

This study demonstrates a method to describe the 3D velocity profile with ultrasound in the aortic annulus with a moving sampling surface. Several investigators have commented on this limitation because of a stationary sampling. Kim et al[21] calculated the underestimation to be 7% of cardiac output in mitral blood flow. In calculations of volumetric flow in the aorta, this underestimation is estimated to 9% of cardiac output (95% confidence interval [CI], 0.4-0.5 L/min) in healthy individuals.[22] Another advantage of our method is a better temporal resolution than reported by Kupari et al,[17] that is, 15 to 22 ms in our study versus 30 to 40 ms, which will enhance the quality of the measurements.

Our study confirms earlier 2D ultrasound studies that described the velocity profile as skewed in the aortic annulus. The ratio of the maximum to the mean velocity at the time of peak flow was higher than what was found with previous color flow Doppler methods in healthy subjects.[13,14] One explanation might be that the sample surface in our study was spherical and not necessarily perpendicular to the aortic root axis compared with the earlier color flow Doppler studies. In systole, blood flow velocities might be detected earlier, in the lateral part of the annulus, rather than toward the septum. Further, because of the sweep-time delay, the change in recorded blood flow velocities from one side of the sector to the other would be maximum 0.17 m/s at 57 frames per second and blood flow acceleration of 10 m/s^2. However, the VTI is unaffected by this and the ratio of the maximum VTI to the mean found in our study was similar to the study by Zhou at al.[14]

The maximum velocities and VTIs showed a tendency to be most often located toward the septum, although there was a variability confirming the results of previous studies.[13,14,17] The mean VTI was located along the brim of the aortic annulus. The reason for the somehow peripheral location of the mean VTI was that blood flow velocities decreased sharply toward zero close to the arterial wall. The blurring of the tissue border in the 2D slice reconstruction of the mean VTI enhanced the impression of a location in the periphery (Figure 2, *C*). This was due to movement of the anatomical structures and some change in shape during the cardiac cycle (Figure 2, *A* and *B*). Several slices were averaged to illustrate the position of the mean VTI.

Our results must be taken into account when calculations of stroke volumes are based on recordings with PW Doppler from a single sample volume. Previous studies have concluded that blood flow velocities in the center of the annulus should be measured with PW Doppler. However, the Doppler sample volume is fixed during recording of blood flow velocities, but the heart is moving. Thus, the PW Doppler volume is not really recorded from 1 particular position in the annulus. According to our results, the mean VTI is located along the brim of the annulus and the ratio of maximum VTI/mean VTI illus-

Journal of the American Society of Echocardiography
April 2002

Table 1 Quantitative assessment of blood flow velocity distribution

Subject No.	Max velocity (cm/s)	Mean velocity (cm/s)	Max velocity / mean velocity	Max velocity time integral (cm)	Mean velocity time integral (cm)	Max velocity time integral/ mean velocity time integral
1	123.3	91.0	1.4	19.6	15.3	1.3
2	97.9	60.9	1.6	20.4	13.8	1.5
3	80.8	60.6	1.3	17.8	14.1	1.3
4	128.0	95.0	1.3	32.1	23.0	1.4
5	124.3	86.2	1.4	23.6	18.8	1.3
6	115.3	80.0	1.4	22.9	16.5	1.4
7	131.6	91.2	1.4	27.1	19.3	1.4
8	99.4	74.1	1.3	19.8	15.2	1.3
9	113.6	57.6	2.0	21.1	14.0	1.5
10	79.7	47.7	1.7	19.0	12.9	1.5
11	103.9	82.2	1.3	21.8	17.8	1.2
12	105.1	80.6	1.3	24.0	18.7	1.3
13	110.7	88.1	1.3	24.3	18.0	1.4
14	111.6	71.0	1.6	27.6	19.7	1.4
15	110.2	97.0	1.1	27.2	21.9	1.2
16	108.2	71.4	1.5	19.7	14.4	1.4
17	114.1	64.6	1.8	28.3	18.7	1.5
Average	109.3	76.4	1.5	23.3	17.2	1.4
Max	131.6	97.0	2.0	32.1	23.0	1.5
Min	79.7	47.7	1.1	17.8	12.9	1.2

Max, Maximum; *Min*, minimum.

trates the range of possible errors because of blood flow measurements in calculations of stroke volumes based on the 2D PW Doppler method.

Several ultrasound methods have been proposed to deal with the problems related to a skewed and nonuniform velocity profile in volumetric calculations. Spatiotemporal integration of blood flow velocities is a way to avoid this obstacle. Kim et al[23] applied a transthoracically multiplane method in calculations of volumetric mitral blood flow in humans and showed close agreement with MRI in the aorta ascendens. Preliminary reports using digital color flow Doppler acquired with multiplane transesophageal probes in volumetric calculations, in vitro or in vivo, in open-chest animals have recently been presented.[24-27] These methods showed close correlation with electromagnetic flow probes.

Initial experiences with heart motion-adapted magnetic resonance velocity mapping of blood velocity distribution have recently been described and were applied to studies of flow downstream of aortic valve prostheses.[28]

Our 3D color flow Doppler method has also been validated in calculations of volumetric flow.[22] The common pitfalls in PW ultrasound methods to calculate cardiac output were avoided, as the 3D method was angle independent, no assumptions about the velocity profile were made, and a moving sample surface was applied. The acquisition of data was fast and easy, and high temporal resolution was achieved. These studies suggest that 3D color flow Doppler imaging may turn out to be a valuable clinical tool in calculation of cardiac output and regurgitant fractions.

However, our study was limited by several factors: It may be difficult to cover the entire region of interest because of a limited acoustic window. The method is not suited to investigate subjects with irregular heart rhythm, such as atrial fibrillation, or those unable to hold their breath for a short period of time. The latter was not a problem in this study but may pose problems to subjects who experience shortness of breath because of pulmonary disease or congestive heart failure. In this study, the postprocessing was performed after all the data from all the subjects were acquired. By evaluating the 3D reconstruction immediately after each recording, a new one could replace the corrupted one. The velocity profile was only close to instantaneous because of sweep-time delay in the color flow Doppler image, but this error was limited by the high frame rate. Only a limited range of cardiac output was investigated. The velocity profile might change depending of the cardiac output.

In conclusion, we have described the 3D velocity profile in the aortic annulus based on a new dynamic 3D color flow Doppler method. High frame rate improved the temporal resolution, and blood flow

velocities were measured through a spherical surface, which followed the annulus throughout systole. The blood flow velocity profile was nonuniform. The maximum velocity and VTI were variably located in the flow area. By using a single sample volume in Doppler measurements of the maximum VTI, errors ranging from 20% to 50% may be introduced in calculations of stroke volumes.

REFERENCES

1. Skjærpe T. Principles of volume flow measurements. In: Roelandt JRTC, Sutherland GR, Iliceto S, Linker DT, editors. Cardiac ultrasound. Sidcup, Kent, England: Churchill Livingstone; 1993. p. 199-205.
2. Kitabatake A, Inoue M, Asao M, Ito H, Masuyama T, Tanouchi J, et al. Noninvasive evaluation of the ratio of pulmonary to systemic flow in atrial septal defect by duplex Doppler echocardiography. Circulation 1984;69:73-9.
3. Kitabatake A, Ito H, Inoue M, Tanouchi J, Ishihara K, Morita T, et al. A new approach to noninvasive evaluation of aortic regurgitant fraction by two-dimensional Doppler echocardiography. Circulation 1985;72:523-9.
4. Lewis JF, Kuo LC, Nelson JG, Limacher MC, Quinones MA. Pulsed Doppler echocardiographic determination of stroke volume and cardiac output: clinical validation of two new methods using the apical window. Circulation 1984;70:425-31.
5. Skjærpe T, Hegrenaes L, Hatle L. Noninvasive estimation of valve area in patients with aortic stenosis by Doppler ultrasound and two-dimensional echocardiography. Circulation 1985;72:810-8.
6. Farthing S, Peronneau P. Flow in the thoracic aorta. Cardiovasc Res 1979;13:607-20.
7. Segadal L, Matre K. Blood velocity distribution in the human ascending aorta. Circulation 1987;76:90-100.
8. Segadal L. Velocity distribution model for normal blood flow in the human ascending aorta. Med Biol Eng Comput 1991; 29:489-92.
9. Paulsen PK, Hasenkam JM. Three-dimensional visualization of velocity profiles in the ascending aorta in dogs, measured with a hot-film anemometer. J Biomech 1983;16:201-10.
10. Kvitting P, Hessevik I, Matre K, Segadal L. Three-dimensional cross-sectional velocity distribution in the ascending aorta in cardiac patients. Clin Physiol 1996;16:239-58.
11. Firmin DN, Mohiaddin RH, Underwood SR, Longmore DB. Magnetic resonance imaging: a method for the assessment of changes in vascular structure and function. J Hum Hypertens 1991;5(Suppl 1):31-40.
12. Klipstein RH, Firmin DN, Underwood SR, Rees RS, Longmore DB. Blood flow patterns in the human aorta studied by magnetic resonance. Br Heart J 1987;58:316-23.
13. Rossvoll O, Samstad S, Torp HG, Linker DT, Skjaerpe T, Angelsen BA, et al. The velocity distribution in the aortic anulus in normal subjects: a quantitative analysis of two-dimensional Doppler flow maps. J Am Soc Echocardiogr 1991;4:367-78.
14. Zhou YQ, Faerestrand S, Matre K, Birkeland S. Velocity distributions in the left ventricular outflow tract and the aortic annulus measured with Doppler color flow mapping in normal subjects. Eur Heart J 1993;14:1179-88.
15. Wiseth R, Samstad S, Rossvoll O, Torp HG, Skjaerpe T, Hatle L. Cross-sectional left ventricular outflow tract velocities before and after aortic valve replacement: a comparative study with two-dimensional Doppler ultrasound. J Am Soc Echocardiogr 1993;6:279-85.
16. Kupari M, Koskinen P. Systolic flow velocity profile in the left ventricular outflow tract in persons free of heart disease. Am J Cardiol 1993;72:1172-8.
17. Kupari M, Hekali P, Poutanen VP. Cross sectional profiles of systolic flow velocities in left ventricular outflow tract of normal subjects. Br Heart J 1995;74:34-9.
18. Berg S, Torp H, Martens D, Steen E, Samstad S, Hoivik I, et al. Dynamic three-dimensional freehand echocardiography using raw digital ultrasound data. Ultrasound Med Biol 1999;25:745-53.
19. Berg S, Torp H, Haugen BO, Samstad S. Volumetric blood flow measurement with the use of dynamic 3-dimensional ultrasound color flow imaging. J Am Soc Echocardiogr 2000;13:393-402.
20. Martens D, Hausken T, Gilja OH, Steen E, Alker HJ, Ødegaard S. 3D processing of ultrasound images using a novel EchoPAC-3D software. Ultrasound Med Biol 1997; 23(Suppl 1):136.
21. Kim WY, Poulsen JK, Terp K, Sloth E, Paulsen PK. New semiautomated Doppler method for quantification of volumetric flow: intraoperative validation with multiplane transesophageal color Doppler imaging. J Am Soc Echocardiogr 1997;10:330-6.
22. Haugen BO, Berg S, Brecke KM, Samstad SO, Sokoerpe T, Slørdahl SA, et al. Measurement of volumetric mitral and aortic blood flow based on a new freehand three-dimensional color flow imaging method: an in vivo validation. Eur J Echocardiography 2000;1:204-11.
23. Kim WY, Poulsen JK, Terp K, Staalsen NH. A new Doppler method for quantification of volumetric flow: in vivo validation using color Doppler. J Am Coll Cardiol 1996;27:182-92.
24. Mori Y, Shiota T, Jones M, Wanitkun S, Irvine T, Li X, et al. Three-dimensional reconstruction of the color Doppler-imaged vena contracta for quantifying aortic regurgitation: studies in a chronic animal model. Circulation 1999;99: 1611-7.
25. Rusk RA, Mori Y, Li X-L, Jones M, Irvine T, Mehwald PS, et al. A validation study of aortic stroke volume using dynamic 4D color Doppler: an in vivo study. J Am Coll Cardiol 2000;35(2,Suppl A):440.
26. Irvine T, Li X-N, Mori Y, Wanitkun S, Li X, Detmer PR, et al. An automatic volume flow method based on 4D digital color Doppler: a computer algorithm tested on an in vitro flow model. J Am Coll Cardiol 2000;35(2,Suppl A):443.
27. Rusk RA, Li X-N, Mori Y, Jones M, Sadcher V, Kenny A. Directly quantifying transmitral stroke volume with digital four-dimensional Doppler: a preliminary in vivo comparison to electromagnetic flowmeter. Circulation 1999;100(18, Suppl I):1-357.
28. Kozerke S, Hasenkam J, Nygaard H, Paulsen P, Pedersen E, Boesiger P. Heart motion-adapted MR velocity mapping of blood velocity distribution downstream of aortic valve prostheses: initial experience. Radiology 2001;218:548-55.