Three-dimensional echocardiography – a novel non-invasive imaging technique: bench or bedside?

PIOTR LIPIEC, JAROSŁAW D. KASPRZAK
Łódź, Poland

LIPIEC P, KASPRZAK JD. **Three-dimensional echocardiography – a novel non-invasive imaging technique: bench or bedside?** Cardiol 2005;14(5):225–230

Three-dimensional echocardiography is a novel non-invasive imaging technique enabling accurate and reproducible analysis of cardiac structure and function. It facilitates the overcoming of common limitations of standard two-dimensional echocardiography, such as measurements requiring far-fetched geometrical assumptions and tomographic data presentation, with its need of difficult mental integration of cardiac spatial structure. Three-dimensional echocardiographic examination can be performed in two distinctly different ways – using off-line reconstruction or real-time techniques. This novel imaging modality is shown to be particularly useful in patients with congenital heart defects and valvular heart diseases. Moreover, it allows accurate measurement of volumes and dimensions. The main limitations of this novel examination method include diminished spatial and temporal resolution, dependency of image quality on acoustic window, and added cost of required equipment.

Key-wordxs: Three-dimensional echocardiography – Left ventricular function – Valvular heart disease – Congenital heart disease

LIPIEC P, KASPRZAK JD. **Trojrozmerná echokardiografia – nová neinvazívna zobrazovacia technika: lavica alebo lôžko?** Cardiol 2005;14(5):225–230

Trojrozmerná echokardiografia je novou neinvazívnou zobrazovacou technikou, ktorá umožňuje presnú a reprodukovateľnú analýzu stavby a činnosti srdca. Uľahčuje prekonať bežné obmedzenia štandardnej dvojrozmernej echokardiografie, ako sú merania, ktoré si vyžadujú osobitné predpoklady a prezentáciu topografických údajov, pre ktoré je potrebná obťažná mentálna integrácia srdcových priestorových štruktúr. Vyšetrenie trojrozmernou echokardiografiou sa vykonáva dvoma odlišnými spôsobmi – použitím off-line rekonštrukcie alebo techniky v reálnom čase. Táto nová zobrazovacia metóda (modalita) sa ukázala ako osobitne užitočná pre pacientov s vrodenými srdcovými chybami a chorobami srdcovej chlopne. Navyše umožňuje presné meranie objemov a rozmerov. K hlavným obmedzeniam tejto novej vyšetrovacej metódy patrí znížené priestorové a temporálne rozlíšenie, závislosť kvality obrazu od akustického okna a ďalšie výdavky pre potrebné zariadenie.

Kľúčové slová: trojrozmerná echokardiografia – funkcia ľavej komory – choroba srdcovej chlopne – vrodená srdcová choroba

Introduction

One of the most commonly used non-invasive cardiac imaging techniques - two-dimensional (2D) echocardiography – allows the viewing of multiple cross-sections of cardiac structures. However, due to the limited number of echocardiographic windows, it may be impossible to obtain a desired cross-section of the heart in any given plane. This limitation may hinder proper assessment of cardiac morphology and function, mainly because such analysis requires tedious mental processes leading to the reconstruction of spatial relationships within the heart, based solely on a limited number of 2D cross-sections. Such mental reconstruction may be extremely difficult in cases of complex abnormal cardiac morphology. Moreover, volume measurements, which are required during the evaluation of cardiac function, necessitate introduction of far-fetched assumptions considering the geometry of heart structures. However, these limitations may be overcome by implementation of a novel technique – three-dimensional (3D) echocardiography.

From Bieganski Hospital, Medical University of Łódź, Poland

Manuscript received March 2, 2005; accepted for publications August 1, 2005

Address for correspondence: Piotr Lipiec, MD, II Chair and Department of Cardiology, Bieganski Hospital, Medical University of Łódź , Kniaziewicza 1/5, 91-347 Łódź,, e-mail: lipiec@ptkardio.pl

Methods

3D echocardiographic examination can be performed in two distinctly different ways – using 3D off-line reconstruction of cross-sectional data or simultaneous volumetric sampling. The older technique – *off-line reconstruction* – requires ECG and respiratory gated acquisition of two-dimensional cross-sections with simultaneous recording of information regarding spatial orientation of registered 2D images (1). Data acquisition may be random or sequential. Random acquisition (freehand scanning) allows unrestricted selection of cutting planes from any precordial acoustic window, while information regarding the transducer position is delivered by locating devices (mechanical, acoustic or magnetic). Sequential data acquisition is performed through a predetermined, computer-controlled, movement of the transducer. Depending on the direction of the transducer movement, different scanning methods may be implemented, varying in the relative orientation of acquired images (1). Linear (parallel) scanning, resulting in a prism-shaped 3D dataset, is performed by moving a probe in a linear direction. Rotational scanning (coaxial images), yielding a 3D dataset conical in shape, is achieved by the rotation of the transducer around the central axis of the array. Fan-like scanning, resulting in a pyramid-shaped 3D dataset, is performed by tilting the transducer at predetermined angles.

Thereafter, using acquired 2D images and corresponding spatial information, a 3D dataset is reconstructed off-line. The results of such a procedure contain averaged data from numerous cardiac cycles with extensive extrapolation. Therefore, the off-line reconstruction method cannot be used for the evaluation of fast-changing processes e.g. during stress echocardiography or contrast perfusion imaging. Moreover, this technique has other well-known limitations, such as new kinds of artifacts, time-consuming examination, post-processing and analysis (2).

These drawbacks have been partly alleviated by the use of first generation *real-time techniques*, but the cost and inferior imaging quality prohibited the dissemination of the technique (3). However, a recent introduction of commercially available ultrasound systems, allowing rapid transition from high-end standard two-dimensional imaging to real-time 3D echocardiographic examination, has opened new perspectives for the technique (4). 3D data are acquired by volumetric scanning with matrix transducer, which contains a large number (up to 3000) of miniaturized piezoelectric elements. The transducer allows a simultaneous acquisition and presentation of data from a pyramidal region of interest in real-time (**Figure 1**) (5). Obviously, that region of interest may be not wide enough for the evaluation of large structures, such as left ventricle. In order to overcome this limitation by creating larger datasets, additional ECG-gated acquisition and fusion of several neighboring datasets can be performed (full-volume mode) (6).

The results of 3D echocardiographic examination are displayed on the monitor – instantaneously during real-time examination and after a less-than-a-minute-long data processing in the case of off-line reconstruction. Depending on the aim of examination, different display modes can be used. The sonographer may choose to view a two-dimensional cross-section of the volumetric dataset in any desired cutting plane (anyplane method) or several coaxial cross-sections (omniplane method) or a number of parallel cross-sections (paraplane method) (7). With the exception of pioneering attempts to employ holographic or stereolithographic methods as a display mode, the examination results are viewed with the use of a standard monitor. Therefore, the display is usually two-dimensional. However, thanks to advanced shading techniques, an impression of anatomical perspective can be created and the sonographer may view a "three-dimensional" reconstruction on the monitor. For this purpose a few rendering techniques are available. The simplest one – wire-frame rendering, used mainly for volume analysis – enables the viewing of a cage-like image of the analyzed cavity. Surface rendering results in the display of the surfaces of the analyzed objects facing the observer as a solid structure. The largest amount of information may be extracted from images constructed with the use of volume-rendering techniques. Such images resemble the true morphology of the region of interest, giving the sonographer an opportunity to view cardiac structures as they would be seen by a cardiothoracic surgeon sectioning the heart. Depending on the image settings (shading, opacity) the structure may appear solid (like surface-rendered images) or transparent, thus providing information about structures underneath the surface (8) Furthermore, 3D image may be freely rotated and sectioned, facilitating a proper visualization and a thorough analysis of the region of interest.

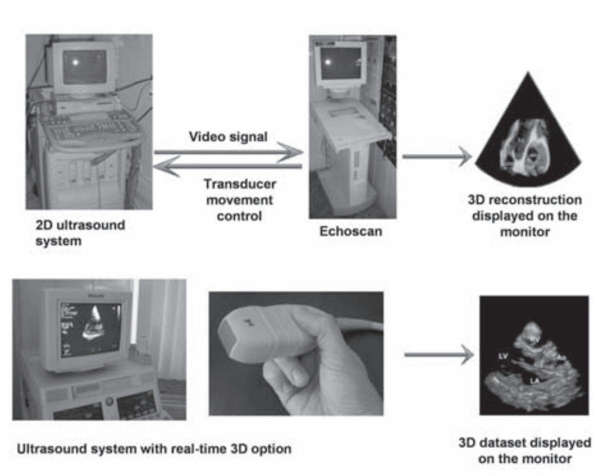

Figure 1 Schematic representation of dataflow in different techniques of three-dimensional (3D) echocardiographic examination: off-line reconstruction technique with sequential (predetermined) data acquisition (*upper panel*) and real-time technique (*lower panel*)

Clinical applications

In clinical practice, volume measurements are among the most frequent sonographers' tasks. In the majority of cases, cardiologists require accurate evaluation of left ventricular end-systolic and end-diastolic volumes and ejection fraction – measurements, which are of great value for the diagnosis and prognosis in patients with various cardiovascular diseases, such as dilated cardiomyopathy. Unlike 2D echocardiography, 3D techniques do not rely on geometrical assumptions simplifying the shape of the analyzed cavity. Such assumptions may lead to inaccuracy, especially in asymmetric, distorted, left ventricles. These limitations also preclude reliable 2D measurements of irregularly-shaped cavities, such as atrial or right ventricular.

Several algorithms have been employed for measurement of cavity volume in 3D echocardiography. One of the earliest was the modified Simpson's rule (disc summation method), which required a paraplane mode of display with subsequent tedious tracing of endocardial border in each cross-section (9). A similar algorithm has been successfully used for left-ventricular mass measurement (10). More recently, dedicated software (such as 4D LV Analysis, TomTec, Germany) has become available, allowing more rapid measurement of left ventricular volume. The algorithm requires endocardial border tracing in several longitudinal slices. Thereafter, a dynamic 3D model of the left ventricle is constructed, allowing volume and ejection fraction calculation (11). Results of volume measurements by 3D echocardiography have been shown to closely correlate with reference methods, e.g. MRI in cases of left and right ventricle (12, 13) as well as the atria (14) (**Table 1**) (15 – 18). In order to reduce time required for the analysis, automatic endocardial border detection algorithms have been developed offering results close to validated manual 3D analysis (15, 19). Obviously, in patients with difficult imaging conditions, endocardial border tracing may be difficult or even impossible. In such cases an intravenous contrast agent (such as Optison) may be used for improving endocardial border definition.

The dynamic 3D model of the left ventricle allows not only the analysis of global volume and systolic function, but also the assessment of regional function (**Figure 2**). Moreover, basing on time-volume curves for each segment the sonographer may evaluate left-ventricular synchrony. This feature may help to identify patients who would benefit from cardiac resynchronization therapy and to assess the outcome of this therapy (20). Furthermore, with the use of current technology tissue Doppler data of the left ventricle, such as strain rate, can be acquired from the apical window and displayed as a bull's eye representation or a 3D color-coded model, which may be scrolled in time and rotated in space.

3D echocardiography has been shown to be particularly useful in patients with congenital heart diseases,

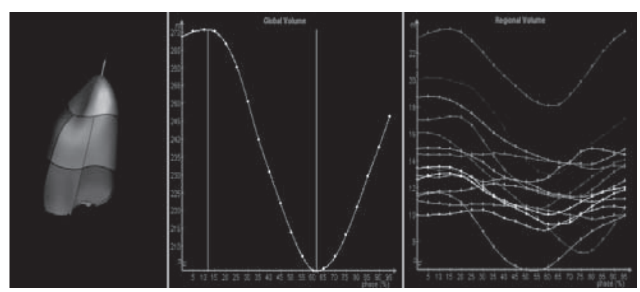

Figure 2 Dynamic three-dimensional reconstruction of left ventricle (*left panel*) facilitates the evaluation of global (*middle panel*) and regional (*right panel*) left ventricular systolic function

Table 1 Results of studies comparing left ventricular volume and function assessment by real-time 3D echocardiography vs. magnetic resonance imaging

Reference	No. of patients	Parameter	Correlation coefficient (r)	Mean difference ± SD	Comments
Kuhl et al. (15)	24	EDV	0,98	- 13,6 ± 18,9 ml	Semi-automatic
		ESV	0,98	- 12,8 ± 20,5 ml	border detection
		EF	0,98	0,9 ± 4,4%	
Jenkins et al. (16)	50	EDV		- 4 ± 29 ml	
		ESV		- 3 ± 18 ml	
		EF		0 ± 7%	
Shiota et al. (17)	19	EDV	0,97	- 43 ± 65 ml	
		ESV	0,94	- 37 ± 67 ml	
		EF	0,98	0,001 ± 0,04%	
Lee et al.(18)	25	EDV	0,99		
		ESV	0,99		
		EF	0,92		

ESV - End-systolic volume, EDV - End-diastolic volume, EF - Ejection fraction, SD - Standard deviation

Figure 3 Volume-rendered reconstruction of secundum type atrial septal defect (*asterisk*) – "en face" view from the right atrium

where it allows more detailed and accurate analysis of cardiac morphology than 2D techniques (21). Such analysis is of the utmost importance in identification of possible candidates for different invasive treatment strategies. For example, in patients with atrial septal defect, "en face" reconstruction of the defect may be attempted to visualize the defect as it would be seen from the right atrium (**Figure 3**). It enables a straightforward assessment of the shape and morphology of the defect and of the surrounding tissue rims, which is essential for intervention planning (22, 23). Furthermore, the outcome of the intervention can be comprehensively evaluated by 3D echocardiography (24).

Similarly, in patients with valvular heart disease 3D echocardiography facilitates the viewing of dynamic reconstructions of the analyzed valves from any given angle. And thus "electronic left ventriculotomy" enables visualization of the mitral or aortic valve as they would be seen by a cardiothoracic surgeon sectioning the left ventricle; "electronic atriotomy" facilitates the viewing of the dynamic reconstruction of the mitral or tricuspid valve from the atrial cavity, and "electronic aortotomy" allows analysis of the aortic valve viewed from the aortic root. A detailed qualitative analysis of leaflets morphology and mobility may be performed on the basis of information combined from those different views (25). For example, in patients with mitral valve prolapse, when leaflets are viewed from the atrial side, a bulging of the prolapsing leaflet into the left atrium occurs during ventricular systole, whereas viewing from the ventricular side one will notice a hollow in that leaflet (23). Thus, 3D images allow exact identification and sizing of the prolapsing scallops (**Figure 4**).

3D techniques are also useful in quantitative analysis of valvular heart disease. Stenotic valve orifice area can be measured in the optimal plane with the use of paraplane method of display or directly in volume-rendered reconstructions. Therefore, a common inaccuracy in 2D echocardiography – overestimation of valve orifice area due to planimetric measurement in suboptimal plane – can be avoided by using 3D techniques (26). Furthermore, 3D reconstructions of the regurgitant valves may be used for a direct measurement of effective regurgitant orifice area (27).

3D color Doppler flow mapping is another diagnostic tool useful in qualitative and quantitative assessment of valvular heart diseases (28). The use of 3D color Doppler flow mapping combined with 3D morphologic data provides clinically relevant supplementary information in patients with valvular regurgitation, enabling exact definition of jet origin and relationship to adjacent structures (23). Moreover, the color reconstructions of the

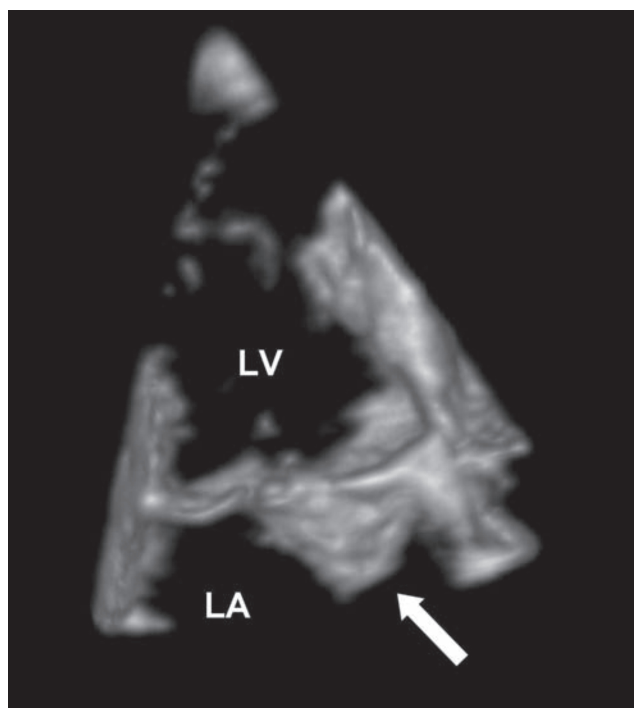

Figure 4 Three-dimensional image of mitral valve (ventricular systolic phase) acquired with real-time technique - evident bulging of the prolapsing scallop of anterior leaflet into the left atrium (arrow) LA - Left atrium, LV - Left ventricle

regurgitant jets can also be analyzed after removing superimposed morphologic data, which allows viewing the jets in their entirety, providing information about spatial geometry, propagation and size of the jets. Furthermore, the shape of the flow convergence region – significantly different from the commonly assumed hemispheric one – can also be appreciated, allowing exact measurement of the proximal isovelocity surface area (29). It has been shown that 3D color Doppler flow mapping enables more accurate quantification of regurgitant jets than 2D techniques, especially in cases of complex asymmetric jets (30).

The shape, size and motion of mitral annulus are important factors determining function of the mitral valve. However, due to spatial complexity a detailed analysis of these features was very difficult using 2D techniques and became feasible with the onset of 3D echocardiography (31). Techniques enabling extraction of mitral annulus images from the whole dataset proved to be particularly useful (32), providing reconstructions of good quality in transthoracic and transesophageal approaches (33). Moreover, 3D echocardiography facilitates functional assessment of the mitral ring in patients undergoing annuloplasty (34).

In our experience, both off-line 3D reconstruction techniques (35) and real-time 3D echocardiography (23) can be incorporated into the routine diagnostic pathway with a high feasibility rate, providing additional qualitative or quantitative information in up to 47% of cases. 3D data of good or demo quality can be obtained in 61 – 73% of cases (23, 35), whereas 5 – 8% of images is of insufficient quality (6, 23). Depending on the series of patients, mean additional time required for real-time 3D examination varies between 10 and 12 minutes (6, 23).

Limitations and future perspectives

As mentioned before, second-generation real time 3D echocardiography has become a solution to many drawbacks of 3D off-line reconstruction technique. However, it should be emphasized that the real-time 3D technology is available only for transthoracic examination and ECG-gated reconstruction is still the only option for 3D transesophageal echocardiography. Furthermore, full volume mode acquisitions and 3D color Doppler flow mapping are not truly real-time, which can sometimes cause minor artifacts. 3D echocardiography is still limited by relatively low temporal resolution, which in certain clinical situations might be a practical limitation e.g. in the process of evaluation of ventricular synchrony (20). Similarly, spatial resolution is usually inferior to that provided by high-end 2D systems. Moreover, 3D image quality, as well as reliable qualitative and quantitative analysis, is highly dependent on the quality of the acoustic window. Finally, the added cost of 3D option can be a limiting factor for some echocardiographic laboratories. Nevertheless, in daily routine practice those limitations are unlikely to outweigh the diagnostic potential of this novel imaging technique, especially given the progress in the abilities and in the user-friendliness of analytic software.

References

1. Roelandt JRTC, Yao J, Kasprzak JD. Three-dimensional echocardiography. Curr Opin Cardiol 1998;13:386–396.
2. De Castro S, Yao J, Pandian NG. Three-dimensional echocardiography: clinical relevance and application. Am J Cardiol 1998;81:96G–102G.
3. Panza JA. Real-time three-dimensional echocardiography: an overview. Int J Cardiovasc Imaging 2001;17:227–235.
4. Wang XF, Deng YB, Nanda NC, et al. Live three-dimensional echocardiography: imaging principles and clinical application. Echocardiography 2003;20:593–604.
5. Sugeng L, Weinert L, Thiele K, et al. Real-time three-dimensional echocardiography using a novel matrix array transducer. Echocardiography 2003;20:623–635.
6. Pepi M, Tamborini G, Pontone G, et al. Initial experience with a new on-line transthoracic three-dimensional technique: assessment of feasibility and of diagnostic potential. Ital Heart J 2003;4:544–550.
7. Salustri A, Kofflard MJM, Roelandt JRTC, et al. Assessment of left ventricular outflow in hypertrophic cardiomyopathy using anyplane and paraplane analysis of three-dimensional echoacardiography. Am J Cardiol 1996;78:462–468.
8. Roelandt JRTC. Three-dimensional echocardiography: the future today! Acta Cardiol 1998;53:323–336.
9. Nosir YFM, Stoker J, Kasprzak JD, et al. Paraplane analysis from precordial three-dimensional echocardiographic data sets for rapid and accurate quantification of left ventricular volume and function: A comparison with magnetic resonance imaging. Am Heart J 1999137:134–143.
10. De Castro S, Yao J, Magni G, et al. Three-dimensional echocardiographic assessment of the extension of dysfunctional mass in patients with coronary artery disease. Am J Cardiol 1998;81(12A):103G–106G.
11. Sugeng L, Weinert L, Lang RM. Left ventricular assessment using real time three dimensional echocardiography. Heart 2003;89(Suppl. III):iii29–36.
12. Vogel M, Gutberlet M, Dittrich S, et al. Comparison of transthoracic three-dimensional echocardiography with magnetic resonance imaging in the assessment of right ventricular volume and mass. Heart 1997;78:12–130.
13. Kasprzak JD, Borkowski M, Kusmierek J, et al. Accurate accelerated 3-dimensional echocardiographic quantification of left ventricular function in unselected patients: a comparison with radionuclide angiography. Acta Cardiol 2002;57:42–44.

14. Poutanen T, Ikonen A, Vainio P, et al. Left atrial volume assessed by transthoracic three dimensional echocardiography and magnetic resonance imaging: dynamic changes during the heart cycle in children. Heart 2000;83:537–542.

15. Kuhl HP, Schreckenberg M, Rulands D, et al. High-resolution transthoracic real-time three-dimensional echocardiography: quantitation of cardiac volumes and function using semi-automatic border detection and comparison with cardiac magnetic resonance imaging. J Am Coll Cardiol 2004;43: 2083–2090.

16. Jenkins C, Bricknell K, Hanekom L, et al. Reproducibility and accuracy of echocardiographic measurements of left ventricular parameters using real-time three-dimensional echocardiography. J Am Coll Cardiol 2004;44:878–886.

17. Shiota T, McCarthy PM, White RD, et al. Initial clinical experience of realtime three-dimensional echocardiography in patients with ischemic and idiopathic dilated cardiomyopathy. Am J Cardiol 1999;84:1068–1073.

18. Lee D, Fuisz AR, Fan PH, et al. Real-time 3-dimensional echocardiographic evaluation of left ventricular volume: correlation with magnetic resonance imaging – a validation study. J Am Soc Echocardiogr 2001;14:1001–1009.

19. Lipiec P, Plewka M, Krzemińska-Pakuła M, et al. Echocardiographic automated quantification of left ventricular volumes and systolic function: a novel clinical tool? Polish J Cardiol 2004;6:311–317.

20. Franke A, Breithardt OA, Rulands D, et al. Quantitative analysis of regional left ventricular wall motion pattern in patients with cardiac resynchronization therapy using real-time 3D echocardiography. Circulation 2003;108:IV–487.

21. Salustri A, Spitaels S, McGhie J, et al. Transthoracic three-dimensional echocardiography in adult patients with congenital heart disease. J Am Coll Cardiol 1995;26:759–767.

22. Maeno YV, Benson LN, McLaughlin PR, et al. Dynamic morphology of the secundum atrial septal defect evaluated by three dimensional transoesophageal echocardiography. Heart 2000;83:673–677.

23. Kasprzak JD, Lipiec P, Drożdż J, et al. Real-time three-dimensional echocardiography: still a research tool or an imaging technique ready for daily routine practice? A pilot feasibility study in a tertiary cardiology centre. Kardiologia Polska 2004;61:303–308.

24. Acar P, Bonhoeffer P, Sidi D, et al. Assessment of the geometric profile of the Amplatzer and Cardioseal septal occluders by three dimensional echocardiography. Heart 2001;85:451–453.

25. Sutaria N, Northridge D, Masani N, et al. Three dimensional echocardiography for the assessment of mitral valve disease. Heart 2000;84(Suppl. II):ii7–10.

26. Kasprzak JD, Nosir YFM, Dall'Agata A, et al. Quantification of the aortic valve area in three-dimensional echocardiographic data sets: analysis of orifice overestimation resulting from suboptimal cutplane selection. Am Heart J 1998;135:995–1003.

27. Lange A, Palka P, Donnelly J, et al. Quantification of mitral regurgitation orifice area by 3-dimensional echocardiography: comparison with effective regurgitant orifice area by PISA method and proximal regurgitant jet diameter. Int J Cardiol 2002;86:87–98.

28. De Simone R, Glombitza G, Vahl CF, et al. Three-dimensional color Doppler reconstruction of intracardiac blood flow in patients with different heart valve diseases. Am J Cardiol 2000;86:1343–1348.

29. Li X, Shiota T, Delabays A, et al. Flow convergence flow rates from 3-dimensional reconstruction of color Doppler flow maps for computing transvalvular regurgitant flows without geometric assumptions: An in vitro quantitative flow study. J Am Soc Echocardiogr 1999;12:1035–1044.

30. De Simone R, Glombitza G, Vahl CF, et al. Three-dimensional color Doppler: a clinical study in patients with mitral regurgitation. J Am Coll Cardiol 1999;33:1646–1654.

31. Kaplan SR, Bashein G, Sheehan FH, et al. Three-dimensional echocardiographic assessment of annular shape changes in the normal and regurgitant mitral valve. Am Heart J 2000;139:37–387.

32. Yamaura Y, Yoshida K, Hozumi T, et al. Evaluation of the mitral annulus by extracted three-dimensional images in patients with an annuloplasty ring. Am J Cardiol. 1998;82:534–536.

33. Ratanasopa S, Bolson EL, Sheehan FH, et al. Performance of a Fourier-based program for three-dimensional reconstruction of the mitral annulus on application to sparse, noisy data. Int J Card Imaging 1999;15:301–307.

34. Dall'Agata A, Taams MA, Fioretti PM, et al. Cosgrove-Edwards mitral ring dynamics measured with transesophageal three-dimensional echocardiography. Ann Thorac Surg 1998;65:485–490.

35. Ciesielczyk M, Drozdz J, Krzeminska-Pakula M, et al. Clinical application of 3-dimensional echocardiography-a 3-year single center experience. Przegl Lek 2002;59:658–662.