Three-dimensional echocardiography: where we are, where we are going

Alessandro Salustri, Jos R.T.C. Roelandt*

*Department of Cardiology, Hospital Sandro Pertini, Rome, Italy, *The Thoraxcentre, Erasmus University Medical Centre Rotterdam, Rotterdam, The Netherlands*

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Three-dimensional reconstruction of the heart has been an important research goal ever since the introduction of two-dimensional echocardiography. Several directions have been followed. Most approaches towards three-dimensional echocardiography are off-line and are based on the sequential rotational scanning and acquisition of multiple cross-sectional images together with their spatial position and orientation using internal coordinate reference systems. From the reconstructed volumetric data set electronic slicing can be performed which allows anyplane and paraplane echocardiography. The availability and versatility using the volumetric data set permits the retrieval of an infinite number of cardiac cross-sections which allow more accurate and reproducible measurements of valve areas, masses and cavity volumes by obviating geometric assumptions. The application of algorithms based on light reflection to the grey scale data provides tissue-depicting information allowing for dynamic volume-rendered display in projection, up till now unavailable in cardiology. This capability decreases variability both in the quality and interpretation of complex pathology among investigators. Emerging clinical experience indicates the strong potential of three-dimensional echocardiography in qualitative and quantitative diagnostic appraisal of various cardiac problems. While the technique is ready for clinical applications, its widespread use can be facilitated by a number of improvements.

Advances in computer technology can be applied to three-dimensional echocardiography offering an exciting opportunity to employ virtual reality and simulation of interventional and surgical procedures, to predict results and plan appropriate therapy. In the future new physiologic parameters will provide additional information and will allow us to address new clinical questions.

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Address:

Dr. Alessandro Salustri

Laboratorio di Ecocardiografia
Dipartimento di Cardiologia
Ospedale Sandro Pertini
Via dei Monti Tiburtini, 389
00157 Roma
E-mail: salustri@jnet.it

Why three-dimensional echocardiography?

While three-dimensional imaging of the heart and its structures is already state-of-the-art with other tomographic imaging technologies including radionuclear, magnetic resonance and computed tomography, progress in three-dimensional echocardiography has been rather slow. In its early stages, three-dimensional echocardiography was applied mainly in volume measurement of the left ventricle using static wire frame pictures which may demonstrate the shape of the ventricular cavity, but does not provide tissue depicting information[1-5]. Recently, along with the rapid evolution in computer technology, three-dimensional echocardiography has grown into a well-developed technique able to display dynamic images of the heart that contain tissue information and show the depth of the structures in their realistic forms[6-8]. These capabilities undoubtedly provide an improved understanding of unpredictable pathomorphology and decrease the variability both in the quality and interpretation of complex pathology among investigators. Advantages of three-dimensional echocardiography are presented in table I. In particular, the availability and versatility using the volumetric data set, showing cardiac anatomy and pathology in projections that have not been possible until now, offer significant advantages.

Approaches to three-dimensional echocardiography

The different approaches to three-dimensional echocardiography are summarized in table II.

Real-time three-dimensional echocardiography. This method developed by the group of Von Ramm[9] of the Duke University is based on novel matrix phased-array transducer technology in which the elements are arranged in a two-dimensional grid. Using parallel processing techniques the matrix array offers steering in both the beam s az-

Table I. Three-dimensional echocardiography: the advantages.

Standardized examination procedure
Off-line (re)examination of patients
Improved quantification of complex volumes
Decrease in interpretation variability among investigators
Electronic cardiotomy and en face views
Diagnosis of unpredictable and complex pathomorphology
New descriptors and parameters (e.g. shape analysis)
Multidimensional imaging
Teaching and virtual reality
Tele-consultation and tele-examination

Table II. Three-dimensional echocardiography: the approaches.

A. Off-line reconstruction
Random scanning
Mechanical arm
Acoustic (spark gap) locator
Electromagnetic
Sequential transducer motion
Linear
Fan-like
Rotational
B. Real-time volumetric imaging

imuth and elevation plane and allows us to cope with the fundamental limitation of the speed of ultrasound in the tissue, permitting us to scan a pyramidal volume immediately (Fig. 1). Cross-sectional images of the pyramidal volume at different depths can be selected on-line (C-scan) (Fig. 2). A first-generation instrument has recently been introduced for clinical evaluation and initial results are promising. However, improvement in image quality is needed for routine clinical application. On-line three-dimensional imaging will find a major application in situations such as myocardial perfusion studies and stress echocardiography.

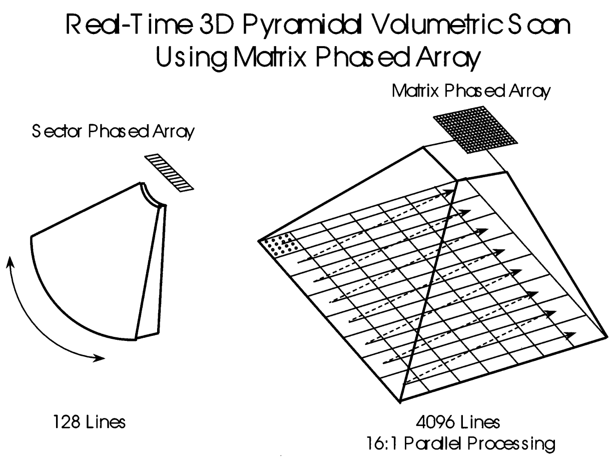

Figure 1. *Real-time three-dimensional pyramidal volumetric scan. The ultrasonic beam is steered in both the elevation and the azimuth plane. Through parallel computer processing it is possible to process several scan lines simultaneously, permitting to scan on-line a pyramidal volume. On the left, a sector phased array is represented for comparison.*

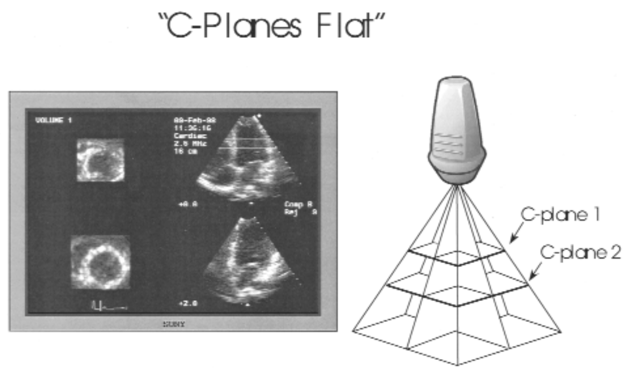

Figure 2. *From the pyramidal volume, cross-sectional images at different depths can be selected on-line (C-scan). This results in on-line any-plane two-dimensional display.*

Off-line three-dimensional reconstruction. At present most clinical experience is with acquisition of a consecutive series of cardiac cross-sectional images using currently available standard transducers and retrospective off-line three-dimensional reconstruction. This approach necessitates the simultaneous registration of the accurate spatial position and timing of the cross-sectional images. The first step of three-dimensional reconstruction is data acquisition which can be random or sequential.

Random data acquisition. Since the images are acquired in random order from different positions, this method offers the unique advantage of using unrestricted free-hand scanning to obtain a series of cut planes from any available precordial acoustic window. Positional information can be obtained with a mechanical articulated arm scanner[10,11], acoustic spark gap[12] or a magnetic location system[13]. The volumetric data set can be used to extract static wire-frame objects or surfaces of selected structures, which are converted into geometric rather than anatomic representations for projection onto a two-dimensional screen. These representations are usually generated from manually-derived contours in the cross-sectional images which is tedious and time consuming. These approaches allow for assessment of structure and surface shapes and for improved quantification of left ventricular volumes.

Sequential data acquisition. With this modality, any ultrasound acoustic window can be used provided an adequately large sequence of images with known relationship to each other and with predetermined movement of the transducer is obtained. When two-dimensional images are acquired in sequence, ECG and respiration gating are necessary for controlled temporal and spatial position image registration. While linear and fan-like scanning have been proposed, at the moment rotational scanning is the most commonly employed method for acquiring images due to the relatively smaller acoustic window compared to the above two methods[14].

• Stepwise acquisition. The rotational acquisition is performed with either multiplane transesophageal probes or a regular surface probe[15-18]. Image acquisition is controlled by a software-based steering logic which considers both cardiac and respiratory cycle variations. The steps for rotational acquisition with a transesophageal probe and image processing are summarized in figure 3. The reconstructed volumetric data set can be sliced to derive cross-sectional images in any desired cutting planes or can be rendered into various forms of three-dimensional images[14-16] (Fig. 3).

• Continuous acquisition. Recently, an ultrafast continuously rotating phased-array transducer has been developed at the Thoraxcentre, which allows the acquisition of 16 volumetric data sets per second[19] (Fig. 4). This makes ECG and respiration gating less critical. Standard ultrasound systems are used and the image quality in the data set is that of state-of-the-art two-dimensional echocardiography. Basic two-dimensional images are digitally stored in the instrument memory and transferred either directly or off-line to a reconstruction and analysis PC. Initial experience indicates that this near real-time approach may become an alternative to real-time volumetric imaging systems in specific clinical conditions.

Image rendering and display

The term rendering indicates the procedure whereby objects are reconstructed in the computed memory.

The availability of data sets containing all cardiac data offers unique advantages. The display and analysis of size, shape and motion of cardiac structures from any desired perspective becomes possible and allows one to address any clinical questions off-line without reexamination of the patient. Unique cardiac cross-sections, difficult or impossible to obtain from standard acoustic windows, can be computed from the data set in any desired plane (anyplane echocardiography) and displayed in cine-loop format. Based on the definition of a specific anyplane image, the paraplane method is used to derive multiple parallel equidistant cross-sectional views through a region of the heart at selected intervals.

Wire-frame or surface-rendered reconstructions of selected structures are obtained from manually-derived contours in cross-sectional images generated from the data set. This approach allows for the assessment of characteristics such as structure and shape and for improved quantification of left ventricular volumes[20]. However, information of the tissue beneath the surface is missing[8].

The use of volume rendering algorithms provides grey scale tissue information in the reconstruction and images that closely resemble the true anatomy of the heart, and represents a significant advance in three-dimensional echocardiography[21]. The three-dimensional effect can be further enhanced by creating rotational sequences of the image upon display.

Clinical applications

Three-dimensional echocardiography has produced promising results from both experimental and clinical studies in the past two and half decades. Favorable experience has been gained in its clinical applications with both transthoracic and transesophageal image data acquisition.

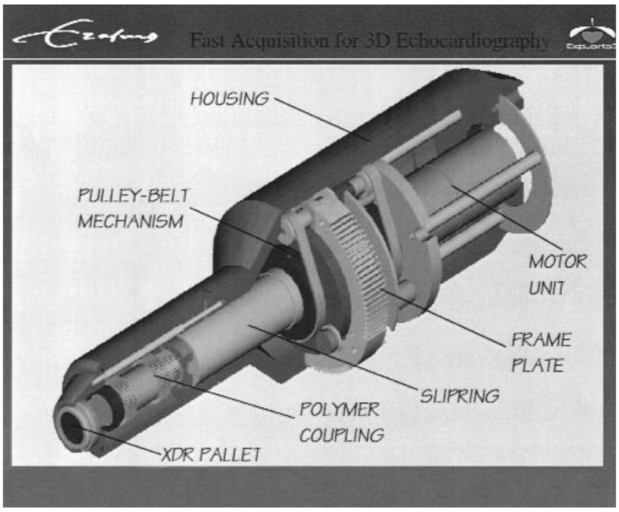

Figure 4. *Schematic drawing of the transducer used for fast acquisition for three-dimensional reconstruction.*

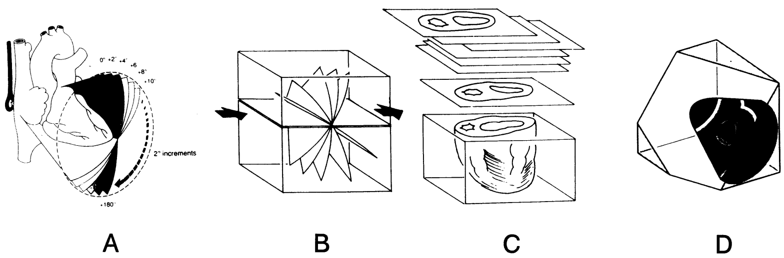

Figure 3. *Schematic drawing showing the steps of acquisition, resampling, conversion, analysis and display of echocardiographic images acquired with rotational technique. Basic cross-sectional images are sequentially (2-degree interval) acquired from a fixed point in the esophagus with a multiplane transducer* (panel A). *The digitized images are then resampled in the correct spatial sequence* (panel B). *Conversion from polar to Cartesian coordinates is necessary for the identification of each individual point in a rectangular coordinate system* (panel C). *These sets are the basic data for off-line anyplane analysis and volume-rendered display* (panel D).

Three-dimensional echocardiography has been proven valuable in congenital heart disease for better evaluation of morphologic abnormalities and understanding of complex spatial relationships[22-26]. Computer reconstruction of en face views of an atrial (Fig. 5) or ventricular septal defect, visualized from its right or left side, not only provides a surgeon s view of the defect before the heart is open but also enables accurate measurement of the dimensions of the defect and of the tissues surrounding the defect, the latter being crucial for planning closed-chest closure of the defect using a transcatheter closing device.

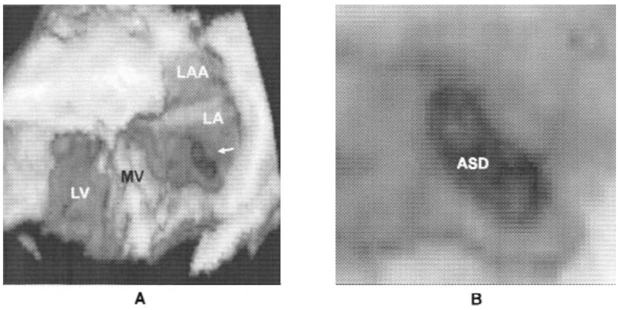

Figure 5. *Unique en face view of a fenestrated atrial septal defect (ASD,* arrow*) type secundum from the left atrium (LA). The image was reconstructed from the three-dimensional data set, using a volume-rendered display. Size, shape, location of the defect and its relationship with other cardiac structures are directly shown in one single view (*panel A*).* Panel B *is a zoom view. LAA = left atrial appendage; LV = left ventricle; MV = mitral valve.*

Both qualitative and quantitative evaluation of valvular heart disease can be improved by three-dimensional echocardiography[27-33]. Anyplane and paraplane analysis of the stenotic valve helps to find the smallest orifice area for accurate planimetry (Fig. 6). Mitral valve prolapse is visualized as a bulging or protrusion on the atrial side together with its exact location and extension, allowing the surgeon to better plan the repair procedures. Three-dimensional echocardiography has been shown to be highly accurate for identifying the flail scallop. Three-dimensional echocardiography may further help in the quantitative evaluation of valvular abnormalities by improved analysis of the proximal flow convergence[34]. Research is currently directed towards reconstruction of regurgitant jets showing the site of origin, trajectory and both the geometric distribution and morphology of the jet[35,36].

Coronary heart disease is one of the most commonly encountered diseases for the cardiologist. Three-dimensional echocardiography has shown its potential in accurate evaluation of volumes and function of the ventricles, in the analysis and quantitative measurements of regional wall motion abnormalities and myocardial perfusion territories using contrast agents[37,38]. Initial experience indicates that three-dimensional visualization of the proximal segments of the coronary arteries is possible.

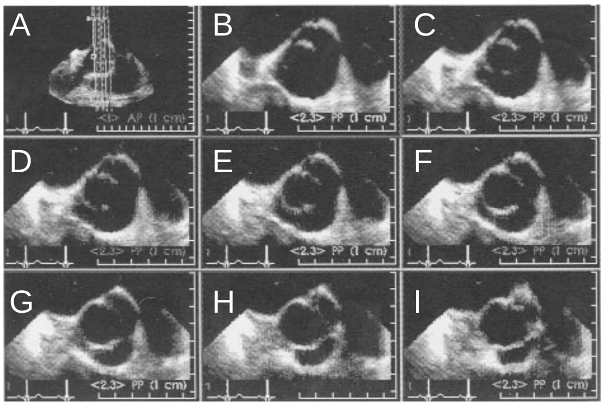

Figure 6. *Paraplane echocardiography using the three-dimensional data set of a patient with bicuspid aortic valve. The original three-dimensional data set is shown in* panel A *and the lines indicate the eighth computer generated parallel short-axis views of the aortic valve represented in* panels from B to I.

Three-dimensional echocardiography has been used in almost all aspects of cardiac disorders and various benefits have been derived. Evaluation of intracardiac or intravascular masses including vegetations, tumors, thrombi or plaques is facilitated both qualitatively (by three-dimensional display of their site, size, attachment and mobility) and quantitatively (by accurate measurement of their dimensions and volumes)[39]. We have also examined aortic diseases such as dilation, aneurysm, dissection or coarctation with three-dimensional echocardiography and incremental information was obtained[40].

Volume quantification. Echocardiography is a widely available clinical method which consents to measure diastolic and systolic volumes and derived parameters, such as ejection fraction. Precision and accuracy of echocardiographic measurements is typically compromised by the user s subjectivity and geometrical assumption about left ventricular shape. The rationale behind the accuracy and reproducibility of volume measurement with three-dimensional echocardiography in comparison with any two-dimensional method is that the three-dimensional approach obviates any geometric assumptions of the shape of the measured object. Good correlations with angiography, magnetic resonance imaging and anatomical measurements (*in vitro*) have been reported[41-46]. At present, ventricular volumes are calculated by manual endocardial tracing of sequential short-axis views derived by parallel slicing through three-dimensional data set at prescribed thickness intervals at either end-systole or end-diastole. Volume quantification is achieved by the summation of the voxels included in the traced area with the subsequent summing of the subvolumes of each slice with known slice thickness (Fig. 7). Stroke volume and ejection fraction of a given chamber can be derived from its end-systolic and end-diastolic volumes. Since this method is time consuming, several investigators have attempted to limit the time requirements by reducing the number of component cross-sections.

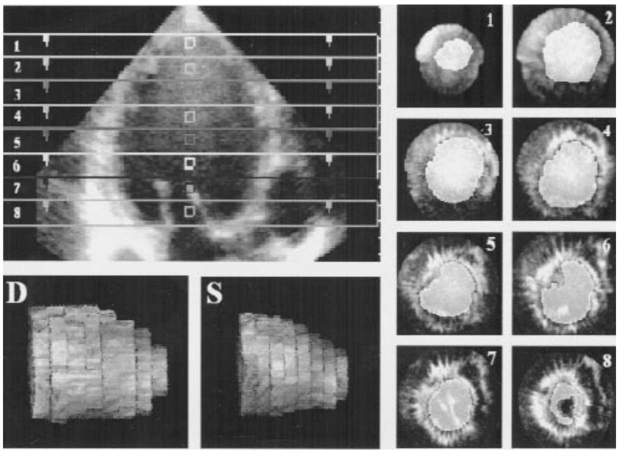

Figure 7. *The principle of left ventricular volume measurement by Simpson s method using three-dimensional echocardiography. A long-axis view* (left upper panel) *is selected as a reference image from the three-dimensional echocardiographic data set. The left ventricle is sliced by paraplane method into eight equidistant parallel short-axis slices spanning the left ventricular cavity from the apex to mitral annulus. The endocardial border of the left ventricle is traced manually in each of short-axis slices 1-8* (right panel). *The volume of each traced region is calculated and the summation of all subvolumes provides the total left ventricular volume at a chosen phase of the heart cycle. D = end-diastolic; S = end-systolic.*

The future

Future developments. More accurate and reproducible measurements together with new physiologic parameters such as wall motion phase analysis, left ventricular curvature analysis for regional wall stress, flow jets and myocardial perfusion will provide additional information and allow us to address new clinical questions which are uniquely three-dimensional (Table III). Indeed, progress in cardiology has often followed new technologies especially when they provide a better insight into pathology and allow new questions to be answered. For these reasons, three-dimensional echocardiography will be an essential part of the clinical practice of cardiology in the future.

Virtual reality in cardiac ultrasound. Three-dimensional echocardiography is the gateway to virtual reality offering great potential for teaching and training, aiding in complex diagnostic situations and assisting in the planning of surgical procedures[47]. At present, three-dimensional reconstructions are still presented in two-dimensional format. These reconstructions can pose interpretation difficulties, principally for the observer in understanding the origins and orientation of the views. Virtual dynamic techniques, known as virtual reality, can assist in the interpretation of three-dimensional presentations of the heart. Virtual reality models are useful in maintaining the spatial information. Virtual reality allows us to dive into a three-dimensional simulation of the heart and is now being introduced into practice for evaluation as a teaching aid, as a permanent reference environment for diagnosis and to assist the surgeon in planning procedures. When the virtual reality model is coupled with real echo data, e.g. during the examination of a patient, an interactive scenario becomes possible in which the operator can select a standardized echocardiographic view, which is defined in the virtual reality model. This view is then also visible in the real echo data from which a three-dimensional reconstruction of the desired standard view can be computed. Identifying landmarks in the real echo data can perform the coupling of the virtual reality model with real echo data.

Cardi-Assist is a European project in cardiology in which virtual reality has a crucial role. This project aims to provide remote support for the diagnosis of cardiac abnormalities, with echocardiography and transmission of data using telecommunication, being pivotal. Part of the Cardi-Assist project will be used to develop a teaching station for sonographers and cardiologists.

Table III. Three-dimensional echocardiography: the perspectives.

Ultrafast acquisition and/or real-time volumetric imaging
Electronic cardiotomy and structure extraction
Heart and structure modeling (stereolithography)
Color-coded regurgitant jets (display and volume analysis)
Dysfunctional mass
Shape analysis and wall stress
Physiologic imaging (motion phase analysis, myocardial perfusion)
New display methods (virtual reality, holography)

Present limitations

Most currently available three-dimensional echocardiographic systems use ECG and respiration triggered image acquisition. This requires 3 to 5 min and in certain circumstances up to 10 min, depending on incremental step, ECG and respiration rate and rhythm and gating range. Artifacts from inadvertent patient or operator movements are more likely when the procedure of image acquisition takes longer. This long acquisition time is a significant limitation in some clinical scenarios such as intraoperative studies, the interventional laboratory, stress echocardiography and contrast perfusion echocardiography. The heart is a moving target relative to the stationary transducer which causes a blur. Non-uniform rotation speed during acquisition and rotational axis deviation (patient movement) may also cause significant artifacts. Real-time three-dimensional echocardiography would allow us to overcome these limitations. New transducer assemblies such as the ultrafast rotating phased-array transducer will bring the acquisition time down to seconds for specific quantitative studies. In addition, with the advances in computer technology, processing and analysis time has decreased from hours to minutes and is targeted to reach seconds in the near future.

Accuracy of three-dimensional displays and computer generated any/paraplane cross-sections from the data sets remains a problem with three-dimensional reconstruction techniques. Structure resolution deteriorates with depth and in the lateral parts of the basic images. With rotational acquisition systems the image accuracy in the three-dimensional volumetric data set varies according to both the angular step and the width of the ultrasound beam. Since the beam width depends on the scan depth and the scan angle, the image resolution will degrade at points further away from the transducer and at a larger scan angle. Currently available experience suggests that the best resolution is gained within the focal region along the central axis of the transducer. Reconstructed images of cut planes distant from the rotational axis will have a reduced reliability although they may look acceptable because of computerized smoothing. This is important for the selection of anyplane images. Electronic interpolation is necessary to fill the gaps between cross-sections in the far field and may be inaccurate. Overall threshold settings for segmentation create artificial structures and/or tissue overgrowth. In addition, three-dimensional image information depends on the two-dimensional scan plane density. At a certain scan depth, an increase in the interval angle will reduce the acquisition time, but at the same time will increase the gaps between consecutive scan planes, resulting in lower sampling data of the volume. This allows for left ventricular volume studies, whereas anyplane studies for structure analysis require a much higher sampling rate.

At present most of the endocardial border tracing is done manually. This is laborious, time consuming and subjective. Automated border detection algorithms are available and initial results show that they reduce the analysis time and allow more accurate calculation of left ventricular volume and function. In addition, endocardial border delineation can be enhanced by using second harmonic imaging or by adding intravenous injections of contrast agents for endocardial border delineation.

Conclusion

Three-dimensional echocardiography provides the clinician with more confidence for the diagnosis of cardiac disease and adds insight into the understanding of complex pathology. It decreases variability both in quality and interpretation among operators. Further developments and improvement for its widespread routine application include faster and/or real-time acquisition, processing and reconstruction and easier and versatile approaches to quantitative analysis. Clinical research must be directed towards identifying those cardiac conditions in which the diagnostic potential of three-dimensional echocardiography is superior or more cost-effective than competing imaging methods such as magnetic resonance. At present, additional three-dimensional information in surgical decision-making and the increasing number of clinical questions that can be addressed and answered can already justify the clinical use of this technique[48,49]. However, the real value of three-dimensional echocardiography will always be intimately dependent on our intellectual contribution: how, when, and in what clinical situation will it have a maximal clinical impact?

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