Transesophageal Real-Time Three-Dimensional Echocardiography
Methods and Initial In Vitro and Human In Vivo Studies

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OBJECTIVES
The purpose of this study was to develop a transesophageal probe that: 1) enables on-line representation of the spatial structures of the heart, and 2) enables navigation of medical instruments.

BACKGROUND
Whereas transthoracic real-time 3-dimensional (3D) echocardiography could recently be implemented, there is still no corresponding transesophageal system. Transesophageal real-time 3D echocardiography would have great potential for numerous clinical applications, such as navigation of catheters.

METHODS
The newly developed real-time 3D system is based on a transesophageal probe in which multiple transducers are arranged in an interlaced pattern on a rotating cylinder. This enables continuous recording of a large echo volume of 70 mm in length and a sector angle of 120°. The presentation of the volume-reconstructed data is made with a time lag of <100 ms. The frame rate is up to 20 Hz. In addition to conventional imaging, the observer can obtain a stereoscopic image of the structures examined with red/blue goggles.

RESULTS
It was shown in vitro on ventricle- and aorta-form agar models and in vivo that the system enables excellent visualization of the 3D structures. Shape, spatial orientation, and the navigation of various catheters (e.g., EPS-catheter, Swan-Ganz-catheter), stents, or atrial septal defect occluders could be recorded on-line and stereoscopically depicted. The size of the echo sector enables a wide field of view without changing the position of the probe.

CONCLUSIONS
Transesophageal real-time 3D echocardiography can be technically realized with the system presented here. The in vitro and in vivo studies show particularly the potential for navigation in the heart and large vessels on the basis of stereoscopic images. (J Am Coll Cardiol 2006; 48:2070–6) © 2006 by the American College of Cardiology Foundation

Although transthoracic real-time 3-dimensional (3D) echocardiography can be realized (1,2), there is still no corresponding transesophageal system for examination of the heart. It can be expected that transesophageal access will lead to a superior real-time 3D imaging of atria and valves as well as segments of the large vessels close to the heart.

The objective of this project was development of a transesophageal echocardiography (TEE) probe that: 1) enables on-line representation of the spatial structures of the heart and large vessels, and 2) enables navigation of medical instruments on the basis of stereoscopic images. We are presenting the technical principles of data acquisition and presentation, the image quality of the new system was tested by in vitro and in vivo studies.

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METHODS
The core of the transesophageal real-time 3D echocardiography (RT3D-TEE) system is a newly designed semi-mechanical transesophageal probe (Sulzer Innotec, Winterthur, Switzerland). Its special design allows for rapid imaging of large volumes of interest, thanks to the use of parallel scanning techniques.

The RT3D-TEE probe consists of a cylinder with 24 transducers (Fig. 1), which rotates in a protective hull filled with oil.

The system uses 5-MHz center frequency; the active aperture of each transducer measures 8 mm. The transducers are arranged in 3 linear groups on 3 sides of the cylinder. The 3 groups are rotated 120° with respect to each other, and in axial direction, they are dislocated relative to each other by 1/3 of the transducer spacing. With this arrangement, 8 planes can be recorded simultaneously in a 120° sector. By completing 1 revolution, 24 planes are recorded. A wedge-like region of 120° and 72 mm in height is acquired in this way with a frame rate corresponding to the number of revolutions/s (i.e., 15 to 20 frames/s). An advantage of this design is the fact that the individual sound elements are well spaced apart and therefore well acousti-
cally uncoupled, which is essential to minimize crosstalk between adjacent tissue slices when applying parallel scanning techniques.

The diameter of the round probe tip, including the protective sheath, is 14 mm. The cross-sectional area is thus only slightly larger than the cross-sectional area of commercial 2-dimensional (2D) TEE probes, which have a tip cross-section of about \(10 \times 14\) mm. However, the transducer is nearly 8 cm long, which results in greater rigidity and potentially more difficult intubation of the esophagus. The flexibility of the probe tip is provided by 2 joints to facilitate insertion of the probe in vivo. Thus, the tip of the probe is divided into 3 segments; the middle segment is 4 cm long, and the proximal and distal segments are 2 cm each. Straightening of the probe occurs automatically, owing to the rotational forces, resulting finally in an echo sector with exactly parallel echo planes.

Safety considerations. The torque of the rotating probe is limited to a low level by means of a mechanical system. This should prevent injury to the epithelium, even if the protective sheath should break. Moreover, the sheath is filled with nontoxic oil in case there should be a leak. There is slight warming of the probe of about 2°C due to the rotation. Heating to more than 41°C is prevented by sensors.

The probe is rotated by a flexible drive shaft. The ultrasonic signals are supplied via a rotating coupling from an electronic unit, consisting of the transmitter/receiver and digitizer module. The digitized data are then sent to a generic PC, equipped with a powerful graphics engine. The conversion from the raw ultrasonic data stream into a series of stereoscopic images is almost entirely carried out by the graphics engine. An advanced volume-rendering algorithm can generate 20 stereoscopic frames per second. The novel rendering procedure operates in the original cylindrical coordinate system that the data are scanned in. With the help of red/blue goggles, the observer obtains true 3D insight, seeing the tissue structure as well as the instrument to be guided.

Agar models of the left ventricle, the aorta, and septum defects were prepared for the in vitro studies. The models were examined in a water tank in which the TEE probe was firmly mounted to a frame. With various medical instruments (EPS-catheter, Biotronik, Berlin, Germany; Swan-Ganz catheter, B. Braun AG, Melsungen, Germany; Amplatz occluder, AGA Medical Corporation, Golden Valley, Minnesota; impeller pump; aortic stent graft), an examination was carried out to determine whether these could be visualized precisely enough with the system and whether the temporal image resolution enables navigation. Dynamic changes of a balloon model were examined in an artificial, pulsatile circulation.

In vivo examinations were made in 1 human subject (U.M.). Local anesthesia with xylocaine-spray was applied to the pharynx. Xylocaine gel was used to lubricate the probe. The probe could be introduced without sedation in \(2\) min. The examination lasted a total of about \(10\) min. Six data sets, each \(45\) s long, were stored on the system memory.

The authors had full access to the data and take responsibility for its integrity. All authors have read and agree to the manuscript as written.

RESULTS

In vitro studies. The RT3D-TEE-System enables excellent spatial imaging of the models of ventricle and aorta (Fig. 2). Thanks to the large echo sector, even large objects like the ventricle model could be completely imaged without moving the probe. Moreover, the large echo sector facilitates the navigation of instruments: as seen in Figure 3, large

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**Abbreviations and Acronyms**

- **3D** = 3-dimensional
- **ASD** = atrial septal defect
- **RT3DE** = real-time 3D echocardiography
- **RT3D-TEE** = transesophageal real-time 3D echocardiography
- **TEE** = transesophageal echocardiography
segments of the catheter of an Amplatz occluder could be imaged; the structures of the occluder are excellently resolved (Figs. 3A and 3B, Video 1 [see Appendix]). Figure 3C shows the RT3D-TEE image of an “atrial septal defect” (ASD) before implantation of an Amplatz occluder. After implantation (Videos 2 and 3 [see Appendix]), it is easy to see how the occluder closes the defect (Fig. 3D). Instruments smaller than an Amplatz occluder were also imaged in size, position, and structure. Figure 4 (Video 4 [see Appendix]) shows an 8-pole EPS-catheter in the ventricle, and even the individual poles of the catheter are imaged. In Figure 5 (Video 5 [see Appendix]), a Swan-Ganz catheter with inflated balloon is placed in the ventricle model. Figure 6 (Video 6 [see Appendix]) illustrates that not only...
the position of the aortic stent in the vessel model but also the thin stent struts can be imaged. Figure 7 (Video 7 [see Appendix]) shows an impeller pump in the ventricle. In addition to the conventional image, a red/blue presentation can be selected with the RT3DE system. With red/blue goggles, the observer obtains a stereoscopic image that facilitates navigation in space. The temporal resolution of 15 to 20 Hz enables adequate imaging of cyclic changes. Video 8 (see Appendix) shows the diastolic and systolic phase of a balloon model in the artificial, pulsatile circulation.

In vivo studies. Figure 8A (Video 9 [see Appendix]) shows a single cut plane of a 3D data set. Fine structures like the atrial septum, leaflets of the mitral valve, and the cusps of the aortic valve are also spatially well resolved. The volume-rendered images show the spatial structures of the heart in 3D presentation (Fig. 8B, Video 10 [see Appendix]). The best image quality was attained in the atria, at the level of the cardiac valves and the basal segments of the ventricles (Figs. 8C and 8D). The temporal resolution of the system enables imaging of dynamic changes during the cardiac cycle (Video 11 [see Appendix]).

DISCUSSION

Technical development of 3D echocardiography to date. This imaging procedure has been developed in several steps since the initial development of 3D echocardiography (“Echo-CT”) (3) in the late 1980s. The broadest use of data acquisition initially involved the rotation procedure on the basis of commercial multiplane TEE-transducers (4). Later, transthoracic data acquisition with the rotation procedure (5) or the freehand technique (6) were also realized. The limited image resolution of these procedures have been clearly improved by recent developments (7,8). The decisive disadvantage of these procedures, however, remains that data acquisition and presentation are not done in real-time.

The introduction of the first phased-array real-time volumetric 3D imaging system (Duke University, Durham, North Carolina) enabled transthoracic real-time acquisition of 3D echocardiographic data sets (9). A breakthrough in the area of transthoracic real-time 3D echocardiography was achieved with the so-called “Live-3D” (Sonos 7500, Philips, Andover, Massachusetts) (1,2). In addition to transthoracic real-time acquisition, simultaneous presentation of perspective images became possible; the spatial image resolution was considerably improved.

RT3D-TEE. In the present study, a system for RT3D-TEE could be realized on the basis of parallel scanning technique. The initial in vitro examinations on models of the left ventricle and aorta as well as initial human in vivo examinations show that the system enables excellent imaging of 3D structures. Like transesophageal 2D echocardiography, RT3D-TEE also delivers the best image quality in the atria, the mitral and aortic valves, and the basal segments.
Figure 7. Impeller pump in the ventricle model. The transesophageal real-time 3-dimensional (3D) echocardiography system enables 2 different types of presentation. (Left) Conventional presentation. (Right) By using stereoscopic goggles, the observer obtains a stereoscopic presentation of the structures examined. The objective of this presentation mode is to facilitate 3D navigation.

Figure 8. (A) Individual cut plane of the 3-dimensional (3D) data set (5-chamber view). Fine structures like the atrial septum, leaflets of the mitral valve (MV), and cusps of the aortic valve (AV) are spatially well resolved. The 3D data set comprises multiple parallel cut planes. (B) Left oblique view of ventricles and atria. Interatrial (IAS) and interventricular septum (IVS) can be recognized as well as the free wall of the right atrium (RA) and right ventricle (RV). The MV is closed; the view is directed toward the left ventricular outflow tract. (C) View through the opened AV. Further, the view passes through the RA to the IAS. The closed MV can be seen in the anterior area of the left atrium (LA). (D) Top view of the atria, the atrioventricular valves, and the AV. The view passes through the LA to the IAS. Anterior and posterior mitral leaflets are visible. The fine edges of the cusps are well-resolved in the area of the AV; the sinus of Valsalva are visible in the 3D image. LV = left ventricle; TV = tricuspid valve.
of the ventricles. Furthermore, we were able to demonstrate that the spatial image resolution is sufficient to depict details of various instruments, like catheters, stents, or occluders. Transducers with higher frequencies could be used in future to further improve the structural resolution in the near field. The reduced signal/noise ratio of more distant structures would probably be acceptable, because high-resolution imaging of the apical segments of the ventricles is less important for the potential clinical applications. The temporal resolution of 15 to 20 Hz enables imaging of cyclic changes as well as on-line navigation of catheters. The frame rate—that is defined by the rotation speed of the probe tip—must, however, be increased for certain questions, such as the quantitative analysis of valve dynamics (7,8). A particular advantage of the system presented is the size of the echo volume. The current transthoracic RT3DE technique still requires fusion of several sector images to record the left ventricle, owing to the small sector. In addition to the usual depiction of volume-reconstructed data on the 2D screen, the system was extended by an alternative visualization mode. The examiner can select a red/blue presentation that, with the appropriate goggles, provides a stereoscopic visualization of the object being examined. This mode creates optimal conditions for navigation in 3D space. In clinical applications, the use of such goggles could, however, be a problem, because the visibility of other monitors would be impaired. Meanwhile, however, stereo-monitors are available that enable stereoscopic presentation without requiring special goggles.

**Perspectives and clinical implications of RT3D-TEE.** Transesophageal 3D echocardiography thus far has had the major disadvantage that reconstruction was performed offline. It was thus used mostly for scientific investigations. An RT3D-TEE system with good spatial and temporal resolution, however, has great potential for numerous clinical applications. This applies both for already-established procedures and for new ones currently under development. For example, navigation of the catheter for electrophysiological studies has been performed thus far with fluoroscopy. On the one hand, the examiner only obtains a 2D summation image of the cardiac structures in this procedure. On the other hand, procedures like the ablation of atrial fibrillation are accompanied by extensive radiation (10,11). Transesophageal real-time 3D echocardiography could thus become an important supplement to imaging in electrophysiology. It would also be a valuable procedure for controlling the intervention in percutaneous implantations of ASD occluders or cardiac valves (12–14). The development of new surgical procedures in the future should enable operations like ASD occlusion or mitral valve repair on the beating heart under 3D echocardiographic control. Sue-matsu et al. (15–18) have demonstrated the feasibility of such procedures in their latest studies, whereby they performed the studies on the model with transthoracic RT3DE systems. As the authors noted, RT3D-TEE would be necessary for clinical applications.

**Conclusions.** This initial in vitro and human in vivo study shows that RT3DE can be technically achieved not only transthoracic but also on the basis of a transesophageal system. The spatial image resolution enables high-quality display of 3D structures. Medical instruments such as catheters, occlusion systems, or stents can be imaged and navigated on-line. Thus, RT3D-TEE could become an important supplementary imaging procedure, because it enables improved navigation without radiation load.

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**REFERENCES**


APPENDIX
For accompanying videos, please see the online version of this article.