Integrated Multimodality Imaging for Structural Heart Disease Intervention

The possibility of combining data from different imaging techniques may facilitate procedural guidance and provide better assessment of anatomic structures.

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Recently, one of the strongest trends seen in the treatment of structural heart disease (SHD) is the transition from open heart surgery to minimally invasive percutaneous procedures with the aim to provide at least equivalent procedural results. This growth of the structural field has led to impressive new technologies for the treatment of patent foramen ovale, atrial septal defect, ventricular septal defect, and patent ductus arteriosus with therapies like paravalvular leak closure, balloon valvuloplasty, mitral valve repair (including different approaches), percutaneous aortic and pulmonic valve implantation, valve-in-valve implantation, and left atrial appendage occlusion. Widening recognition among clinicians and patients' desire for less-invasive treatment options have led to a rapidly growing number of structural heart interventions during the past several years.[1-3]

Today, minimally invasive percutaneous procedures already allow for the treatment of selected patients who are not able to undergo surgery due to their unacceptable high risk. In the near future, new interventional technologies may even enable the treatment of conditions for which no adequate therapeutic option is currently available. The rapid development of percutaneous structural heart technologies is accompanied by new challenges in regard to imaging modalities. Fluoroscopy alone does not provide adequate soft tissue imaging, thus more advanced imaging technology is required to support fluoroscopy in diagnosing and guiding procedures.

Noninvasive imaging techniques, such as echocardiography, magnetic resonance imaging (MRI), and multidetector computed tomography (MDCT) technologies, are currently the preferential imaging modalities to diagnose SHD, and they play a major role in selecting patients for specific structural heart interventions. The application of these imaging tools, including three-dimensional (3D) imaging modalities, leads to improvements of multiplanar soft tissue imaging, enhanced pretreatment target lesion roadmapping and guidance, and the ability for immediate multiplanar posttreatment assessment.

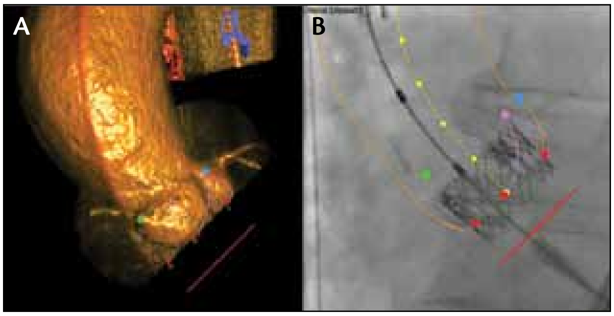
In percutaneous structural heart interventions, the combination of new interventional tools, improved visualization through multimodality imaging, and the understanding of heart structures and function is beginning to have a major impact on operator confidence. Current studies are evaluating the impact of operator confidence on procedural success rates and outcome measures, such as procedure time and radiation exposure. The fusion of different advanced imaging modalities in real-time has the potential to further improve patient selection, as well as procedural planning and success rates, and to shorten the procedure time. In this article, we focus on new integrative multimodality imaging approaches and matching different noninvasive imaging modalities with live x-ray to provide a single data set that incorporates valuable information about each of the combined imaging modalities.

THE ROLE OF IMAGING DURING SHD INTERVENTIONS

Unlike surgeons, interventionists performing SHD interventions do not have the advantage of studying anatomy in the setting of open heart surgery. Furthermore, as opposed to vascular interventions that are performed in the well-defined space of small branching vascular trees, and where fluoroscopy is usually sufficient to guide the procedure, percutaneous structural heart interventions imply navigation in an open 3D space (relatively large cardiac chambers). Imaging modalities such as echocardiography (including two-dimensional [2D] and 3D modalities), MRI, MDCT, and x-ray play a vital role in providing information on the exact location and anatomy of the target structures and access ways in order to safely guide wires, catheters, and devices into target regions of the heart. Due to challenging visual-spatial relationships, SHD interventions are optimized by having a team that includes interventionists and experts in echocardiography and advanced imaging. Interventionists and imagers performing SHD interventions require training with new and unique navigational devices and should have expertise in structural and spatial cardiovascular anatomy and pathology. They also need to learn new procedural skills and gain familiarity with novel image guidance technologies.

Two-dimensional x-ray fluoroscopy and cineangiography remain the standard for visualization in catheterization laboratories. However, fluoroscopy alone is limited in the visualization of soft tissue and 3D structures. Therefore, the advantages of additional noninvasive imaging modalities are made use of and have already been widely adopted into the process of patient selection, procedural guidance, and assessment of procedural results. Multimodality imaging (the side-by-side registration of data rendered by different noninvasive imaging modalities such as echocardiography, advanced CT technologies, and MRI) increases diagnostic accuracy by combining anatomic, morphologic, and functional information. Thus, some of the limitations of each imaging modality when used alone can be overcome.

Advances in software and hardware development during the past few years have facilitated the integration of various imaging modalities into a single data set, resulting in real-time fusion imaging after registration (ie, proper alignment and scaling) of the two-image datasets. Ruiz et al[4] recently reported on the feasibility and usefulness of preacquired computed tomographic angiography images (four-dimensional reconstructions), which are displayed in the catheterization lab adjacent to the fluoroscopy images. Providing



(Courtesy of Siemens Healthcare.)

Figure 1. The syngo DynaCT technique is used during TAVR with an Edwards Sapien transcatheter heart valve (Edwards Lifesciences, Irvine, CA). Panel A demonstrates an example of a segmented aortic root that was automatically created by the software. The software detects and marks the coronaries (red and green dots in A and B) and derives a circle parallel to the plane spanned by the three lowest points of the aortic cusps (see three red dots in A and B). Visually, this circle degenerates to a straight line if the three lowest cusp points are aligned (see red line in A and B). In panel B, an overlay of the 3D segmentation onto the real-time fluoroscopic image is shown.

pretreatment roadmapping facilitated probing of paravalvular leaks, and the fused images were helpful in guiding left ventricular puncture when a transapical approach was used for paravalvular leak closure. In addition, MRI fused with x-ray has been shown to be feasible for SHD interventions in animal models during ventricular septal defect closure procedures[5] and mitral cerclage annuloplasty.[6]

INTEGRATED MULTIMODALITY IMAGING APPROACHES

Fused Imaging Technologies During Transcatheter Valve Procedures

Accurate patient selection for transcatheter aortic valve replacement (TAVR) is crucial to optimize results and to minimize complications. The peri-interventional, multimodality imaging approach for TAVR currently includes echocardiography, MDCT, and MRI in addition to conventional fluoroscopy.[7-18]

Preprocedurally, aortic valve annulus dimensions, aortic valve anatomy, and aortic root dimensions are precisely assessed. Furthermore, access ways (peripheral arteries and thoracic aorta), left ventricular function (including thrombus assessment), and coronary artery anatomy are evaluated.

Current advances in imaging technology already permit the combined use of imaging techniques for planning and guiding TAVR procedures. In vitro evaluation has demonstrated the feasibility to guide TAVR procedures by using real-time MRI matched with x-ray images.[19,20]

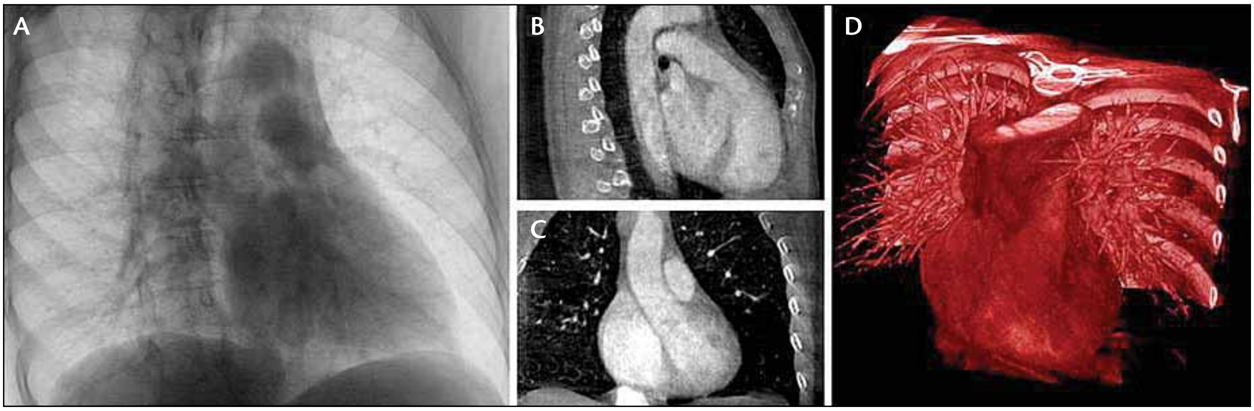


Figure 2. A C-arm CT prototype system was used to create this series of images. Panel A shows a frame from the rotational angiogram involving 180° rotation immediately after central venous contrast injection. Panels B and C show two corresponding slices from the resulting cone-beam 3D reconstruction. Panel D shows the 3D volume rendering. Reproduced with kind permission from Springer Science+Business Media: Int J Cardiovasc Imaging, Potential role of three-dimensional rotational angiography and C-arm CT for valvular repair and implantation, 2011;27:1205–1222, Schwartz JG, Neubauer AM, Fagan TE, et al.[27]

Moreover, advances in rotational angiography enable 3D reconstruction of the aortic root, which makes measurements of the aortic annulus and distances to the coronary arteries before and during the TAVR procedure possible.[21-23] The DynaCT technique (Siemens Healthcare, Erlangen, Germany) allows for an overlay of 3D reconstructions onto x-ray live images. It has been shown that this technique is feasible and helpful in structural heart interventions, including paravalvular leak closure[24] and pulmonary vein stenting,[25] and it is also a promising tool for guidance of aortic valve positioning and deployment.[26]

Based on a periprocedural C-arm CT acquisition, the syngo Aortic ValveGuide software (Siemens Healthcare) automatically segments the aortic root and identifies an orthogonal view plane. Furthermore, it detects and marks the coronary ostia, the nadir of the sinuses, and a central line of the aorta. A circle is derived parallel to the plane spanned by the three lowest points of the aortic cusps (Figure 1). Visually, this perpendicularity circle degenerates to a straight line if the three lowest cusp points are aligned, which corresponds to an optimal perpendicular angulation for valve implantation. No additional fluoroscopy is needed to find this projection, as the C-arm angulation can automatically be synchronized with the 3D view. Whereas the software's standard view evenly spaces the noncoronary, right coronary, and left coronary cusp, different perpendicular projections can be selected. The resulting C-arm angles can automatically be transferred to the angiography system, which will then automatically move to the desired angulation.

An additional overlay of the 3D segmentation onto the real-time fluoroscopic images facilitates orientation during the valve implantation (Figure 1B). The 3D volume is inherently registered to the fluoroscopic images as both images are acquired on the same system. The overlay dynamically adapts to C-arm rotations and table movements.

Another system is the HeartNavigator system (Philips Healthcare, Andover, MA), which enables 3D reconstruction of 2D CT data sets that are overlaid with the live fluoroscopic image to provide real-time 3D insight during procedures.

In a first step, a preacquired computed tomographic angiogram of the chest is loaded into the HeartNavigator system. The aorta, aortic root, and left ventricle can be automatically segmented (isolated) from surrounding structures to better visualize the anatomic structures of interest. Markers are then placed on the coronary ostia and the nadir of the sinuses. Multiple virtual device templates can be used to determine the proper size of the device. Afterward, the software determines the most suitable projection for the procedure. Additional projections can be stored and recalled if needed. Finally, aortic angiography is performed, and the previously segmented aortic root is matched manually to the patient´s anatomy. The HeartNavigator image visualizes the aortic root in various ways and simultaneously provides information on the distribution of calcification.

During the procedure, the live fluoroscopic image may be matched with the 3D image of the ascending aorta to show the exact position of catheters and devices in relation to the reference image. The C-arm moves to the fluoroscopic projection chosen, and the 3D image automatically follows the orientation of the C-arm in real time.

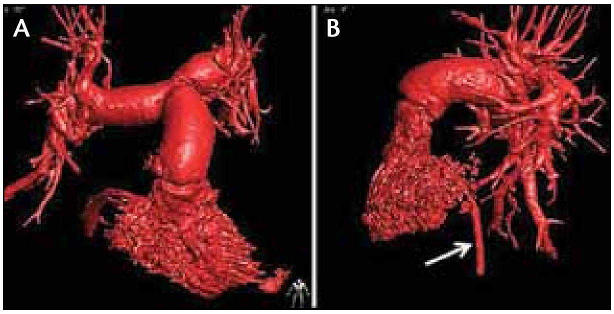


Figure 3. Segmentation to show the right ventricle and pulmonary artery. C-arm CT produced this 3D volume rendering and is displayed in two views. Note the reconstructed catheter entering the right ventricle from the inferior vena cava in the right panel (white arrow). This patient had a surgically placed conduit in the main pulmonary artery. Reproduced with kind permission from Springer Science+Business Media: Int J Cardiovasc Imaging, Potential role of three-dimensional rotational angiography and C-arm CT for valvular repair and implantation, 2011;27:1205–1222, Schwartz JG, Neubauer AM, Fagan TE, et al.[27]

In addition to the monitor that shows only the live fluoroscopic image, the overlay image of the 3D image data and live fluoroscopy are shown on a separate monitor.

Usually, multiple low-contrast aortograms are obtained using different projections to select the optimal plane for device deployment. Additionally, repeated contrast injections during valve delivery are required to confirm optimal placement. The new features of the syngo DynaCT Cardiac and the HeartNavigator technology may potentially lead to reduced radiation exposure, as well as a reduced volume of contrast media. Furthermore, an improvement in valve placement, a shortened procedural learning curve, and fewer complications due to suboptimal valve positioning may be expected.

A new direction in CT imaging is called "C-arm CT." Flat-panel digital x-ray detectors mounted on an advanced C-arm gantry capable of rapidly rotating or spinning around the patient in an arc are used for in-room cone-beam reconstructions. Figure 2 provides an example from development work carried out at the University of Colorado Hospital, which is working with scientists from Philips Healthcare.[27] The images can be shown as 3D renderings, and the structures of interest can be immediately extracted using the procedure room workstation (Figure 3). Although the current spatial resolution does not match MDCT and contrast administration has to be taken into consideration, the cone-beam reconstructions can be done with less radiation and allow for automatic registration with live fluoroscopy. For interventions, this allows fusion of live fluoroscopy and extracted information from the C-arm CT reconstruction to facilitate placement of devices and positioning of balloons (Figure 4).

Echocardiography and Live X-Ray Overlay

Preprocedural assessment, periprocedural guidance, and postprocedural assessment of percutaneous interventions for SHD currently heavily rely on echocardiography. Echocardiography has many advantages over other advanced imaging modalities (MRI, MDCT) because it is mobile and can be performed at the bedside, in the catheterization laboratory, in the cardiovascular intensive care unit, in the emergency department—any place that can accommodate an ultrasound machine. Furthermore, echocardiography allows for the live performance of imaging immediately before, during, and after a procedure. It also uses no ionizing radiation.

Echocardiography for patient selection and guidance during percutaneous structural heart procedures has evolved from transthoracic 2D echo guidance of percutaneous balloon mitral valvuloplasties, for example, to more complex procedures, such as device closure of congenital defects, left atrial appendage occlusion, valve repair and replacement, or the closure of paravalvular leakages. In this context, echocardiography is continuously evolving and improving. Because 2D technologies are limited in the visualization of complex 3D structures by nature, 3D echocardiography (particularly 3D transesophageal echocardiography [TEE]) has recently become an important

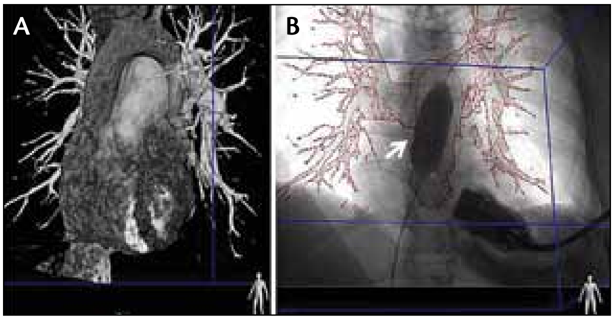


Figure 4. C-arm CT imaging with live fluoroscopy overlay during pulmonary valvuloplasty. Panel A shows the 3D volume rendering of the entire heart and great vessels. Panel B shows the extracted surface of the right ventricular outflow tract and pulmonary artery with fluoroscopic overlay. The outline of the pulmonary artery from the 3D volume rendering is all that is used for the overlay allowing the operator to optimize balloon positioning (white arrow). Reproduced with kind permission from Springer Science+Business Media: Int J Cardiovasc Imaging, Potential role of three-dimensional rotational angiography and C-arm CT for valvular repair and implantation, 2011;27:1205–1222, Schwartz JG, Neubauer AM, Fagan TE, et al.[27]

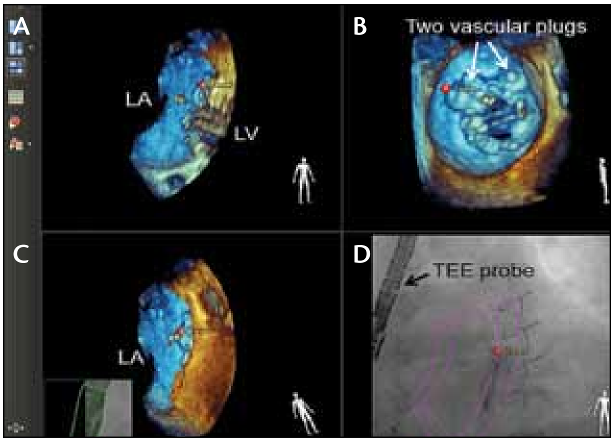


Figure 5. An example of using the EchoNavigator during paravalvular leak closure of a mitral bileaflet mechanical valve. Panels A and B show the 3D TEE volumetric data presented in two views, thus providing the interventionist with a comprehensive display to facilitate the performance of the intervention. The human figure icon represents the perspective of each displayed ultrasound image. In panel C, a portion of the TEE probe with the green outline indicates correct registration. Also in this panel is the 3D TEE image in the same orientation as the fluoroscopic image. The magenta outline (D) is the calculated 3D ultrasound dataset shown as an overlay on the live fluoroscopic images. Finally, a red dot present in all four panels marks the position of the paravalvular leak thus facilitating the crossing of the leak and device deployement.

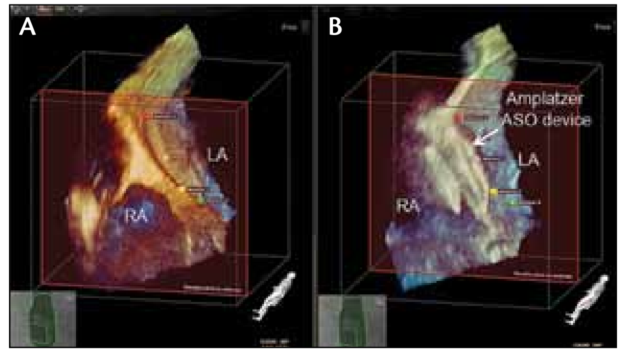


Figure 6. An example of using the EchoNavigator during secundum atrial septal defect closure. In this two-panel figure, an Amplatzer ASO closure device (AGA Medical Corporation, Plymouth, MN) is shown from a steep left anterior oblique caudal projection. The image was cropped using the tableside mouse (red panel representing the cropping plane). These two representative images show the device with the left disc flat against the septum (A), and after cropping both discs are seen with the rims of tissue between the discs (B). Note the four colored markers that had been placed at the beginning of the procedure to mark the plane (ie, border) of the left atrial side of the defect. These markers also were displayed on live fluoroscopy and helped the correct alignment of the left disc to the plane of the defect during deployment using fluoroscopy alone.

adjunct in patient selection and is, in some cases, critical for intraprocedural guidance in percutaneous structural heart interventions. Complex 3D structures and completion of tasks during SHD procedures require interaction with moving targets such as heart valves, catheters, wires, and devices that are frequently difficult to visualize in one plane. Three-dimensional TEE provides more detailed information about the anatomy and facilitates the manipulation and alignment of devices to the targets, thereby increasing the odds of achieving procedural success.

Consequently, there is an increasing reliance on 3D TEE for structural heart interventions. Three-dimensional echocardiography is recommended for the guidance of a number of transcatheter procedures (eg, MitraClip [Abbott Vascular, Santa Clara, CA] implantation, transcatheter aortic valve implantation, paravalvular leak closure, atrial septal defect closure, and left atrial appendage closure).[28]

Interventionists and echocardiographers performing SHD interventions see different perspectives of the target structure, and they orientate themselves in different ways that make communication between them challenging. The echocardiographer must provide 3D image data that are most appropriate and useful to the interventionist and improve the process of orientation. However, it is up to the interventionist to register the results of the 3D images in the 3D space of the patient's heart. Misunderstandings in this communication may lead to errors in device maneuvering and, subsequently, suboptimal results.

The newly developed EchoNavigator system (Philips Healthcare) may further facilitate procedural guidance by matching echocardiographic and fluoroscopic images in real time (Figure 5). Technology that automatically recognizes and tracks the position and the shape of the TEE probe in the fluoroscopic image form the basis of this novel technology. Whenever fluoroscopy is used, the EchoNavigator is able to identify the exact position of the TEE probe by tracking the shape and the direction of the probe within the fluoroscopic image, thus enabling an overlay of the 3D TEE volume in the fluoroscopic image. The echocardiographic view can then be orientated in line with the fluoroscopic image. Once a synchronized view of the echo and fluoroscopic image is achieved, the system automatically tracks and follows the C-arm rotation. Specific cardiac structures or lesions that can be visualized by 3D TEE imaging, but not by fluoroscopy, can be marked in the TEE image (Figures 5 and 6). This labeling is automatically transferred to the equivalent position in the fluoroscopic image and thus enables targeting of defined cardiac structure or defects. This makes fluoroscopic guidance unique in knowing where the target is located on the x-ray image no matter how the gantry is rotated. Tableside controls allow the interventionist to manipulate the 3D TEE datasets, including cropping to expose structures of interest (Figure 6).

In our experience, the EchoNavigator system holds tremendous potential to guide structural heart interventions. We found it feasible and helpful in different kinds of mitral valve procedures, including MitraClip implantation and closure of paravalvular mitral leaks in paravalvular aortic leak closure, in any procedure where a transseptal puncture is required, in left atrial appendage occlusion procedures, and in device closure of septal defects. The EchoNavigator system received FDA approval in March 2013.

CONCLUSION

Catheter-based treatment of SHD is a rapidly progressing field, as increasingly complex diseases can be treated with percutaneous repair. This highlights the increasing need for more detailed information on 3D cardiac structures and defects. Merging data from different noninvasive imaging modalities (MDCT, C-arm CT, MRI, x-ray, and echocardiography [2D and 3D]) provides enhanced functional and anatomical information in real time.

Although only limited clinical data are available at present, the possibility of combining information rendered by different noninvasive imaging techniques in one single data set may facilitate guidance of procedures by supporting the understanding of the spatial relation between the different imaging modalities, thus, making it easier to interpret and understand the anatomical structures as shown by the different imaging tools. By enabling orientation in 3D cardiac chambers, anatomy and device orientation, and by simplifying navigation and steering of wires, catheters and delivery systems device positioning and placement may be facilitated and procedure time, the volume of iodinated contrast media and radiation exposure may potentially be decreased. The effect on clinical outcomes has to be proven in further studies. ■

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