T. Fagan, M.D.

MULTIMODALITY 3-DIMENSIONAL IMAGE INTEGRATION FOR CONGENITAL CARDIAC CATHETERIZATION

Thomas E. Fagan, M.D.[a]; Uyen T. Truong, M.D.[a]; Pei-Ni Jone, M.D.[a]; John Bracken, Ph.D.[a,b]; Robert Quaife, M.D.[a]; Anas A. Abu Hazeem, M.D.[a]; Ernesto E. Salcedo, M.D.[a]; Brian M. Fonseca, M.D.[a]

[a]University of Colorado, Aurora, Colorado; [b]Philips Research North America, Briarcliff Manor, New York

Abstract

Cardiac catheterization procedures for patients with congenital and structural heart disease are becoming more complex. New imaging strategies involving integration of 3-dimensional images from rotational angiography, magnetic resonance imaging (MRI), computerized tomography (CT), and transesophageal echocardiography (TEE) are employed to facilitate these procedures. We discuss the current use of these new 3D imaging technologies and their advantages and challenges when used to guide complex diagnostic and interventional catheterization procedures in patients with congenital heart disease.

Background

Cardiac catheterization remains the standard diagnostic technique for assessing both anatomy and physiology in congenital heart disease (CHD). Fixed projection angiography (FPA) is the mainstay for guiding congenital cardiovascular interventions. However, FPA has limitations in soft tissue visualization and precise characterization of complex structures such as segmental branch pulmonary arteries, coronary arteries, and anomalous or stenotic pulmonary veins. These limitations are due in part to simultaneous opacification of overlying structures, foreshortening of structures if the projection is not perfectly aligned, and the inability to visualize structures without injection of contrast.

Integration of 3-dimensional (3D) image data sets with fluoroscopy can potentially overcome limitations of 2-dimensional (2D) angiography for visualizing complex vascular structures and can facilitate accurate diagnoses as well as guide interventional procedures. The use of 3D images obtained from 3D rotational angiography (3DRA), CT, and MRI was originally developed for neuroradiographic endovascular procedures[1-3] but has played an increasing role in cardiovascular medicine for anatomic delineation[4-7] and electroanatomic mapping.[8] Rotational angiography (RA) and 3DRA have emerged as promising modalities applicable to congenital cardiac diagnosis.[7,9] Additionally, integrated 3D images from 3DRA, CT, and MRI overlaid onto live fluoroscopy are now being used for roadmaps to guide CHD diagnostic and interventional procedures.[5, 6, 10] The potential benefits of integrating 3D images into fluoroscopic procedures for CHD are many, including: (1) improved diagnostic and interventional efficacy, (2) reduced overall radiation exposure, (3) reduced contrast dose, and (4) reduced procedural time.[11-13] All of these are particularly advantageous in the pediatric population. Parallel to this, 3D transesophageal echocardiography (3D-TEE) is currently being applied to CHD catheterization procedures. This technology allows real-time anatomic visualization of soft tissue structures and catheter guidance within the beating heart.

Rotational Angiography and 3DRA

Rotational angiographic images are acquired with the Allura imaging system (Philips Healthcare, Best, The Netherlands) using a fully automated 240˚ C-arm rotation in the axial plane from 120˚ right anterior oblique to 120˚ left anterior oblique, over 4 seconds and at 30 frames/second, during an expiratory breath-hold. This produces multiple 2D X-ray image projections of high temporal and spatial resolution, though still limited to a 2D format. During the C-arm rotation, a timed contrast injection is performed to uniformly opacify the vascular anatomy of interest for the duration of the cine acquisition (Table 1). We have not used right ventricular pacing to reduce contrast burden, as described by others,[14] as this reduces cardiac output.

	Site of injection	Mode of injection	Contrast (cc/kg)	Saline (cc/kg)
PA	RV/MPA	Power	2 cc/kg	1 cc/kg
AO	Aorta/LV	Power	2 cc/kg	1 cc/kg
CPC	Fontan / Glenn	Power +/- hand	1 cc/kg	0.5 cc/kg

Table 1. Basic contrast injection protocols for anatomy of interest. Note that contrast volume was diluted by 1/3 with normal saline to increase injectate volume for uniform opacification. PA: pulmonary artery; AO: aorta; CPC: cavopulmonary connection.

3-Dimensional RA Reconstructions

Reconstruction of the 2D X-ray projection images from RA into a 3D image volume set (using a 3DRA XtraVision workstation from Philips Healthcare) is similar to that of a CT scanner. Unlike an electrocardiogram-gated CT image, however, 3DRA images are captured throughout various phases of the cardiac cycle during the 4 seconds. Automatic 3D reconstruction occurs immediately after the rotation is complete, requiring less than 30 seconds to be generated. Spatial resolution of these reconstructions is comparable to the spatial resolution of the 2D images used to generate them. The reconstruction images can be optimized by a process of manual windowing/leveling and by segmentation (Figure 1). Once generated, these reconstructions can be rotated in three dimensions to determine optimal views of the anatomy of interest.

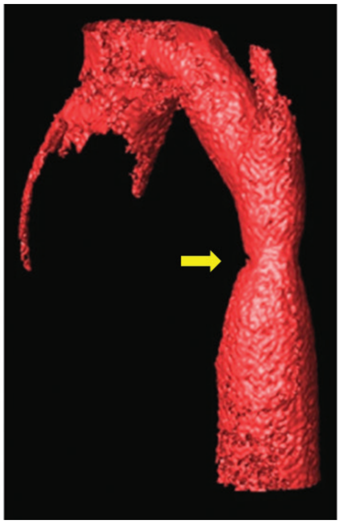

Figure 1. Three-dimensional rotational angiography (RA) of an aortic coarctation (arrow) from an RA.

Multiplanar Reformat

After a 3D image volume set has been generated, it is possible to display 2D image slices from several orientations simultaneously. Known as multiplanar reformatting (MPR), this allows the user to scroll through the reconstructed volume one slice at a time in any orientation (Figure 2).

Advantages and Diagnostic Utility

Major advantages of 3DRA are the ability to visualize complex cardiovascular anatomy from multiple projections and visualize structures from views not possible with a single FPA. This is particularly true for coronary arteries or branch pulmonary arteries in lesions such as tetralogy of Fallot, pulmonary valve atresia, and single-ventricle anatomy. One RA acquisition allows 240° visualization around the axial plane of the patient (Figure 3 A, B). Additionally, MPR and 3DRA images obtained from the same acquisition allow anatomic assessment from essentially every angle (Figure 3 C, D). Table 2 is a summary of patient data based on anatomy of interest for which we applied RA technologies. Different than the axial RA acquisition, several coronary "swing" acquisitions are also available where the C-arm gantry moves through a pattern incorporating the standard projections used to assess the coronary tree. These angiograms, however, do not currently allow MPR or 3DRA.

Though 3DRA techniques for CHD are being used more frequently, there is limited data evaluating the anatomic accuracy and diagnostic utility of these technologies.[7, 9, 14, 15] 3DRA appears to provide at least diagnostic-quality images in 70% to 79% of studies.[7, 9] Quantitative analysis of branch pulmonary arteries was found to be accurate compared to similar analysis of FPA.[14] In a comprehensive review of our use of 3DRA, we documented at least diagnostic quality in more than 79% of studies and superior diagnostic quality (providing additional information) in more than 50% compared to FPA (Table 3).[7] This, however, included our early experience, so we are confident that the rate of inferior studies

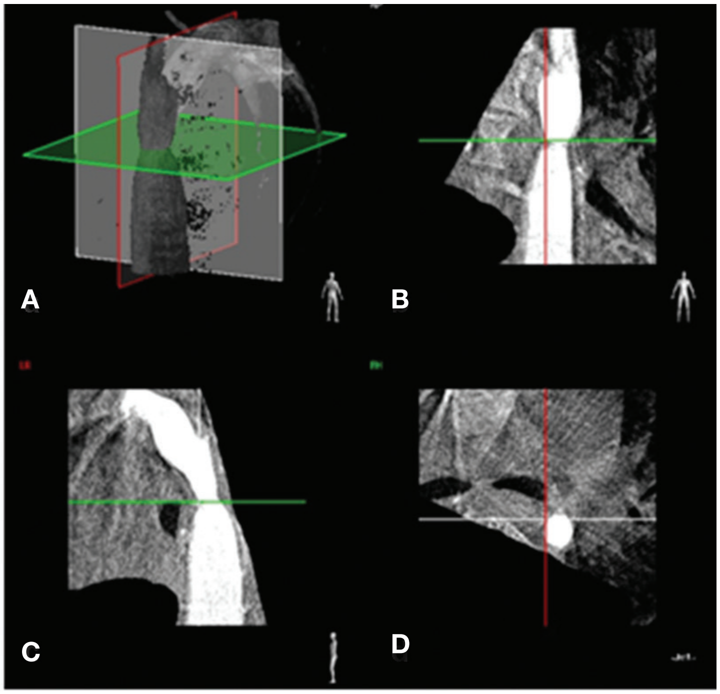

Figure 2. Multiplanar reformatting from a rotational angiogram showing an aortic coarctation. (A) The 3-dimensional (3D) reconstructed volume is shown. The three rectangles show scrolling planes that can be moved independently through the 3D volume to show a specific 2D image slice in one of three orientations: Coronal (white rectangle), axial (green rectangle) and sagittal (red rectangle). (B) Coronal view of 2D image slices through the volume. (C) Sagittal view of 2D image slices through the volume. D) Axial view of 2D image slices through the volume.

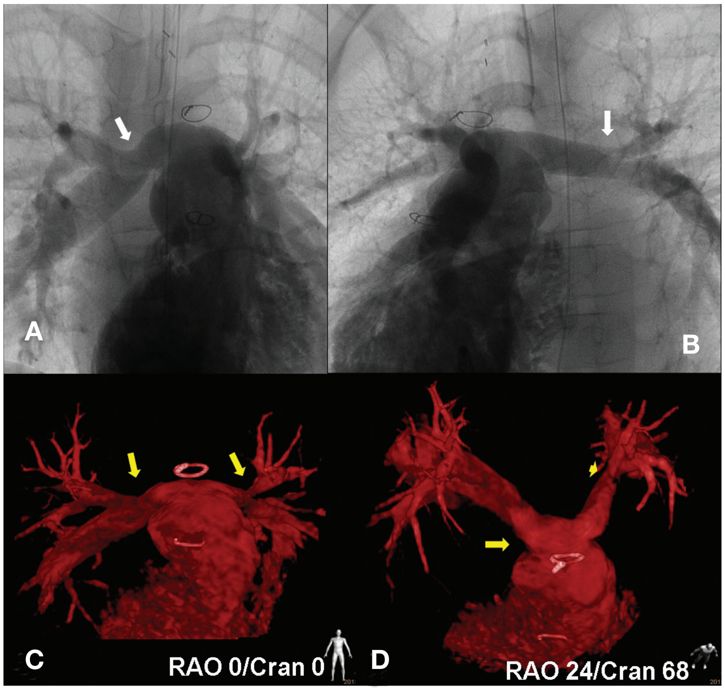

Figure 3. Images from a right ventricular (RV) rotational angiography (RA) in a patient with d-transposition of the great arteries after an arterial switch operation. (A) Right anterior oblique projection showing stenosis of the distal right pulmonary artery (RPA) (arrow). Note the anatomy of the distal main PA (MPA) and left PA (LPA) cannot be clearly visualized because of overlying contrast-filled structures. (B) Left anterior oblique projection showing mild tapering of the distal LPA (arrow). Note again the anatomy of the distal MPA, RPA, and even the orifice of the LPA cannot be visualized clearly. (C) Three-dimensional (3D) RA from the same RA seen from the straight PA view. The anatomy of the dilated MPA again is not defined. Only the distal branch PAs can be seen (arrows); more significant stenosis of the distal LPA is apparent and the moderate RPA stenosis is again seen. (D) The 3DRA image is rotated to a steep cranial view (projection not possible with the angiographic C-arm). Stenosis of the distal MPA (arrow) and more severe stenosis of the distal LPA (arrowhead) is visualized.

	Median age	Median weight	Contrast
Pulmonary artery (N = 51)	2.2 years (1 day-48.4 years)	11.4 kg (3.6-74 kg)	1.9 cc/kg +/- 0.66
Aorta (N = 19)	1.7 years (0.1-17.2)	11.4 kg (3.7-76 kg)	1.7 cc/kg +/- 0.66
CPC (N = 34)	1.2 years (0.5-8.9)	14.5 kg (6.4-106.5 kg)	1.1 cc/kg +/- 0.49
Others (N = 10)	8.9 years (0.4-27.6)	29.5 kg (4.9-76.3 kg)	0.3 cc/kg +/- 0.9

Table 2. Patient data categorized by anatomy of interest. CPC: cavopulmonary connection

n = 114	I	D	S	D+S
RA	21%	27%	52%	79%
3DRA	18%	16%	66%	82%
MPR	17%	21%	63%	84%

Table 3. 3-dimensional rotational angiography modalities rated for diagnostic quality compared to fixed projection angiography. RA: rotational angiogram; 3DRA: 3-dimensional rotational angiography; MPR: multiplanar reformat; I: inferior quality; D: diagnostic; S: superior quality.

will diminish over time. We have now learned specific techniques for optimizing images (e.g., simultaneous contrast injection in both limbs of a Fontan circuit) and specific lesions for which this technology is poorly suited (e.g., patent ductus arteriosus).

3DRA Catheter and Interventional Guidance

Rotational angiography images are automatically registered to, or in geometric correspondence with, the X-ray C-arm coordinate system, which allows the system to track the spatial relationship of all points within the X-ray field, including table position. Therefore, 3DRA images can be manipulated to define optimal projections to guide further catheter manipulations, and 3D images can also be superimposed over live fluoroscopy to produce 3DRA roadmaps

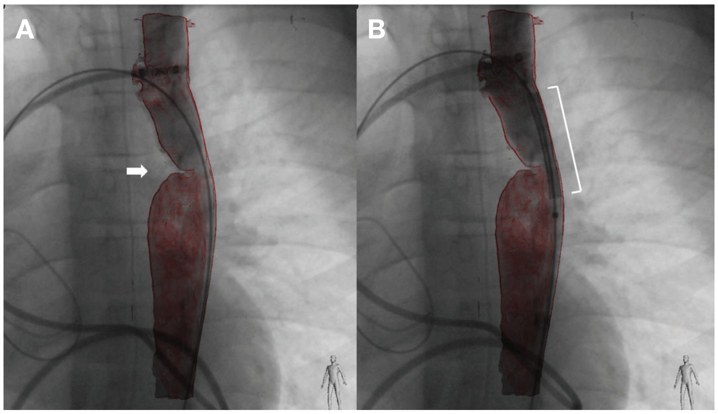

Figure 4. (A) Descending aortogram with 3-dimensional rotational angiography (3DRA) roadmap (red) in a patient with coarctation of the aorta (arrow); contrast angiogram confirms accuracy of overlay anatomy and registration. (B) 3DRA roadmap used for precise stent positioning (bracket).

Planned intervention (n)	Median age (years)	Median weight (kg)	Median contrast (cc/kg)
Transcatheter pulmonary valve (12)	19.1 (7.1-32.9)	65.5 (40-113)	1.6 (0.8-2)
Pulmonary artery stent (16)	5.1 (0.4-26.8)	15.1 (6.5-78)	1.9 (0.8-2.7)
Pulmonary artery balloon dilation (22)	1.9 (0.2-17.5)	11.7 (4.5-52)	1.8 (0.5-2.8)
Coarctation stent (10)	11.9 (7.4-17.4)	44.7 (26.8-85)	1.6 (0.4-2)
Coarctation balloon dilation (5)	0.7 (0.3-6.2)	7.5 (5-21.6)	2.3 (2-2.8)
Other (22)	2.5 (0.2-20.2)	10.7 (4.5-55.8)	1.5 (0.1-2.2)

Table 4. Procedures using 3DRA – roadmapping. Patients = 81; Rotations = 85; Interventions = 87.

Rating	Number (%)
Superior	59 (69.4%)
Similar	18 (21.2%)
Inferior	6 (7.1%)
Disadvantageous*	1 (1.2%)
Not rated	1 (1.2%)

Table 5. Operator rating compared to FPA alone (rotations=85)
*With early prototype, 3DRA image lost after 2 segmentation attempts. There has not been a similar occurrence.

(3DRA-R) (Figure 4). These 3DRA-R follow detector movements and magnification changes to optimally guide catheter manipulations and device placements.[6, 10, 16] Tables 4 and 5 summarize our current use of 3DRA-R as a valuable tool to guide CHD interventions.

3D Computed Tomography Roadmap

Computed tomography is unique among 3D imaging modalities in that it produces high resolution images of both the vasculature and the airway, allowing for easy segmentation and registration as discussed below.[17] At the University of Colorado Hospital and Children's Hospital Colorado, we have been investigating the use of CT in the interventional suite in acquired and congenital heart disease.[17] From January 2009 to February 2012 we used the X-CT prototype system (Philips Healthcare), and since February 2012 we are using the HeartNavigator prototype (Philips Healthcare). We are now exploring its utility in valve implantation in the aortic (transcatheter aortic valve implantation) and pulmonary position.[17] A commercial version of the HeartNavigator is FDA-approved for use in patients with structural and congenital heart disease in the United States. In addition, the *syngo* DynaCT Cardiac System (Siemens AG Healthcare, Forchhiem, Germany) is also commercially available and has been used for cardiac anatomic delineation.[4]

Unlike the 3DRA technique, which uses the fluoroscopic system to acquire 3D images with a known relationship to subsequent 2D fluoroscopic images, CT roadmapping requires appropriate registration of a segmented preprocedure CT volume with the fluoroscopic system. Multiple approaches to registration have been described, including intracardiac catheter manipulation, alignment of the cardiac contour, alignment of the patient's spine, and identification of the pulmonary venous ostia.[8] At our institution, we have early experience using 3DRA or fixed-plane angiography in orthogonal planes to register a preprocedure CT scan. In both of these methods, the intraprocedure imaging is used as a guide to overlay the segmented CT volume. In an attempt to minimize radiation exposure for the registration procedure, we now segment the trachea and carina on CT images, which can then be aligned with live orthogonal fluoroscopic images of the airway. Segmentation is performed on HeartNavigator with an automated software package that allows for manual correction prior to an interventional study (Figure 5).

In our case series, we used CT roadmapping in a wide variety of congenital heart lesions (Table 6), and two-thirds of the cases involved the right-sided cardiac structures. Roadmapping was found to be particularly helpful for guidance and deployment of stents and/or balloons in the pulmonary vasculature to treat pulmonary stenosis percutaneously (Figure 6).

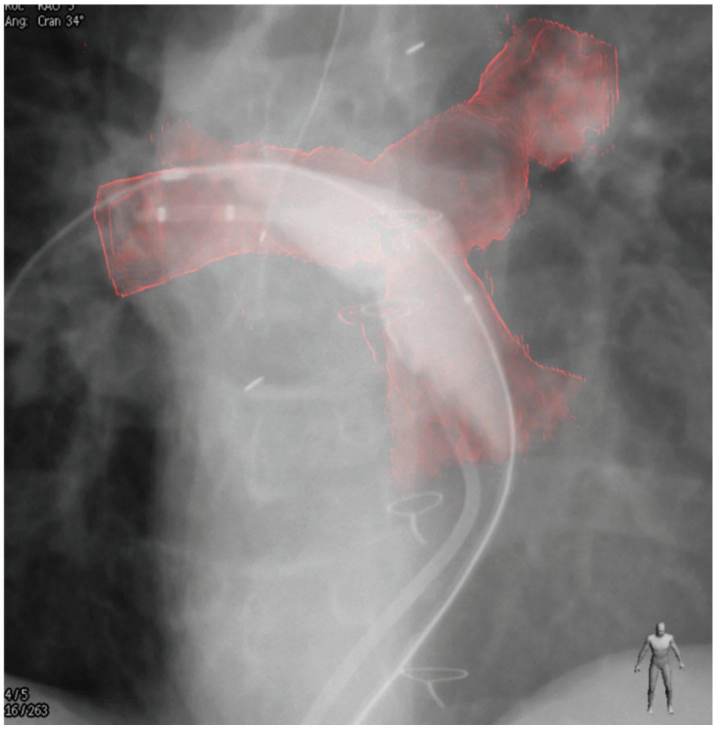

Figure 6. Computed tomography roadmap image over live fluoroscopy (red) used to guide balloon dilation of a stenotic right ventricle to pulmonary artery conduit.

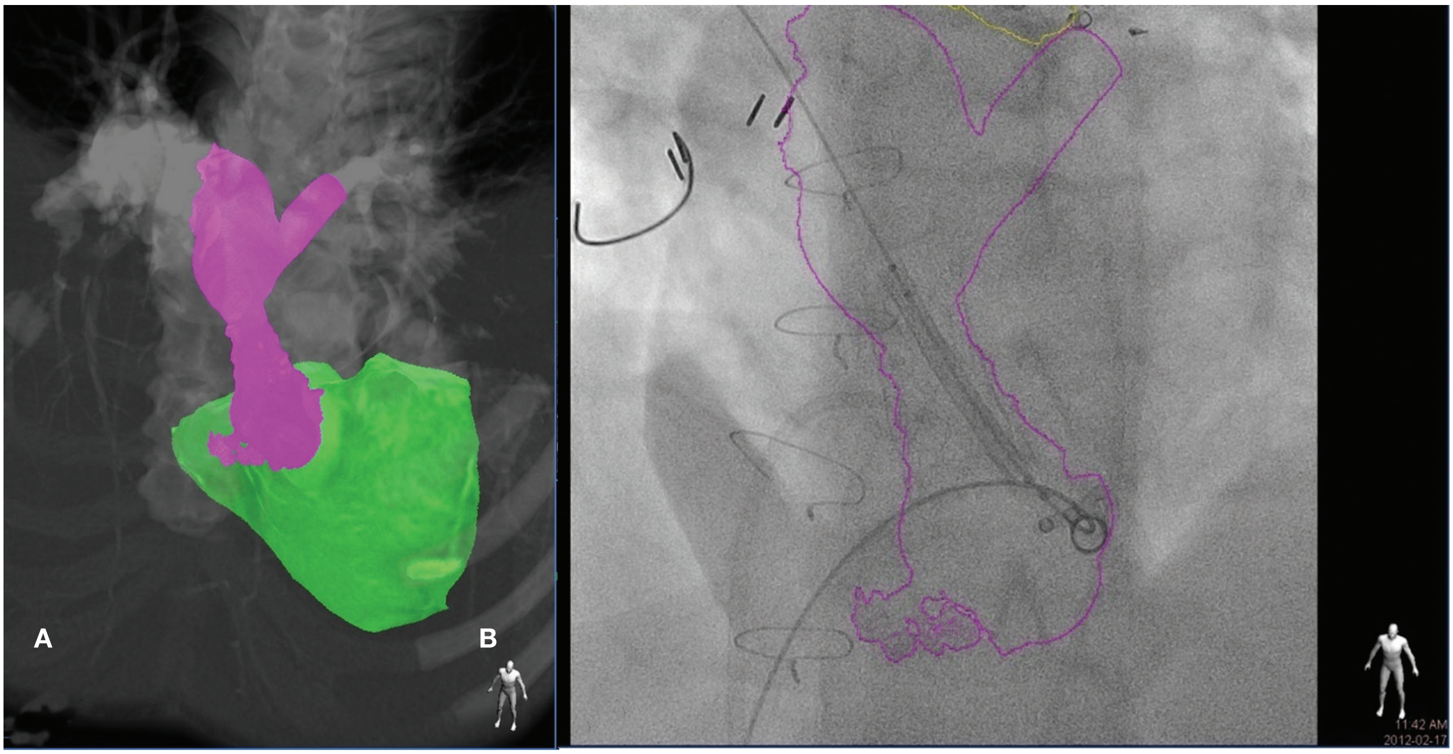

Figure 5. Computed tomography (CT) roadmapping in an adult patient with d-transposition of the great vessels with stenosis through the right ventricle to pulmonary artery (RV-PA) conduit. (a) Segmentation of the anatomy. The green segment represents the RV. The lavender segment represents the stenotic conduit and extends into the proximal branch PAs. (b) Registration of the segmented CT image for live fluoroscopy roadmapping (lavender outline) used for stent delivery within the stenotic conduit.

	Procedure	Age (yrs)	Weight (kg)	Comments
1	RPA stent	34	72.2	Center line; excellent registration
2	LPA revascularization	15	68.0	
3	LPA stent	26	70	
4	LPA revascularization	16	68.1	
5	BT shunt revascularization	39	92.6	
6	Transcatheter Pulmonary valve	18	69.4	Roadmap excellent
7	Transcatheter pulmonary valve	50	74.4	Registration failed; physicians need further system training.
8	MPA balloon dilation post ASO	17	58.6	Segmentation delay; roadmap adequate
9	Pulmonary vein stents	41	68.1	Roadmap excellent

Table 6. CT-roadmapping: cardiac lesion and demographic data. RPA: right pulmonary artery; LPA: left pulmonary artery; BT: Blalock-Taussig; MPA: main pulmonary artery; ASO: arterial switch operation.

Magnetic Resonance Imaging Roadmap

Roadmapping can also be accomplished by using preprocedure MRI angiography. Similar to CT roadmapping, the goals of MRI roadmapping are 2D fluoroscopy optimization, catheter guidance, and 3D visualization of complex anatomy. In a population of patients who often require repeated catheterizations, MRI roadmapping is advantageous as it does not require additional ionizing radiation or iodinated contrast agents.

At the University of Colorado and Children's Hospital Colorado, we are investigating the use of MRI roadmapping for cardiovascular intervention in patients with CHD and have used this technique on a total of 10 cases (Table 7). The technical aspects of MRI roadmapping can be separated into MRI acquisition, segmentation of the MRI, and registration to create a fused image or roadmap.

MRI angiograms were obtained on a 1.5-T Siemens Avanto scanner (Siemens Medical Solutions, Erlangen, Germany) using a volume interpolated breath-hold examination (VIBE). This sequence was acquired as a venous phase with excellent signal in both arteries and veins in addition to enhancement of the airways. MRI images were post-processed prior to the catheterization procedure using a semiautomated segmentation program (HeartNavigator prototype). Compared to segmentation of CT images, MR segmentation is less automated because MRI signal intensity is relative while CT signal intensity is fixed to the Hounsfield scale. As a result, the user is required to identify vessels of interest for segmentation. Segmentation is then accomplished using growing regions that include vascular structures of similar signal intensity. After this process, some manual manipulation of the segmented volume is usually required.

	Procedure	Age (yrs)	Weight (kg)	Comments
1	Coarctation of Aorta / Diagnostic	13	46.7	Registration difficult; changed airway imaging
2	Coarctation Balloon Dilation	6.5	17.3	Registration difficult; roadmap helpful for procedure
3	DORV; PA	0.33	6.6	Fiducial marker-fell off; anatomy exact; registration off
4	LPA Stent	23	96.5	Registration long; Registration not exact but helpful
5	PA / IVS; Diagnostic/Coil Collateral	2.75	13	Fiducial markers; roadmap excellent
6	Coarctation Stent	12	58.5	Roadmap worked very well; images lost late
7	Coarctation Stent	16	35.7	Patient moved; roadmap worked well prior
8	Peripheral PA Dilations	2	12.6	Fiducial markers; registration good; poor MR vascular differentiation
9	Aortic Jump Graft Stent	41	73.7	Roadmap excellent
10	Occlusion Persistent Levo-Cardinal Vein	7	31	Anatomic detail and registration excellent

Table 7. MRI-roadmapping: cardiac lesion and demographic data. DORV: double outlet right ventricle; PA: pulmonary artery; LPA: left pulmonary artery; IVS: intact ventricular septum.

Multiple techniques for registration of the 3D segmented volume to the fluoroscopic system have been described.[8] We opted for two techniques. For patients who underwent MRI and cardiac catheterization during the same anesthesia, we used skin fiducial markers (Brainlab, Feldkirchen, Germany) for image registration. These markers consist of an adhesive-backed plastic cradle that holds a marker bead. The markers were placed in a triangle pattern with apices at the lower and upper margin of the midline sternum and midsternum to the left of midline. Care was taken to place the markers in the field of view of both the MRI and fluoroscopy. The markers were placed over the bony sternum to minimize registration error due to movement of the skin relative to internal organs.[18] During MRI acquisition, the fiducial markers contained a vitamin E bead. At the time of catheterization, these beads are switched for iodinated contrast beads, with care taken so as not to disturb the location of the adhesive cradle. The fiducial markers make image registration straightforward and extremely accurate (Figure 7). This is an important advantage in infants, where a small registration error would be noticeable. Every attempt was made to place the patient in the same position in both the catheterization laboratory and MRI scanner to aid in image registration.

In patients who underwent a preprocedure MRI well in advance of the catheterization, we performed image registration using the airway. As mentioned previously, the VIBE sequence enhances the airway. As a part of the segmentation process, the airway was segmented in addition to the vessels of interest. The segmented airway was then used to register the segmented volume to the fluoroscopy system. Both registration techniques require comparison of either fiducial markers or airway to two orthogonal noncontrast fluoroscopy acquisitions. We have opted for these techniques to avoid additional contrast and radiation doses required for previously described methods.[8]

Similar to CT roadmapping, MR roadmapping has significant advantages in cardiac catheterization of patients with complex CHD. Once the MRI data set is registered, catheter manipulation can occur without contrast administration, which is traditionally used to visualize vessels. The MRI roadmap also allows the operator to optimize the fluoroscopy angulation to highlight particular anatomic features, avoiding a trial and error approach that can result in multiple cine runs to adequately profile the anatomy. As a 3D technique, MRI roadmapping is an elegant way to show complex 3D structures that can be difficult to appreciate with 2D imaging alone. Finally, the VIBE MR acquisition images recirculated contrast, which can highlight vascular structures that are difficult to image with direct contrast injection in the catheterization laboratory.

MR roadmapping is somewhat more time intensive and technically challenging than CT roadmapping. It requires a relatively specialized image acquisition to highlight the airway, and segmentation requires more user input compared to CT roadmapping. While this technique is promising, it would benefit from more automated segmentation and registration. We are currently developing MRI acquisitions that better highlight the airway and vessels for easier segmentation and registration. There has been reported work in automated registration with the fiducial[19] markers and image characteristics that could potentially streamline the process.

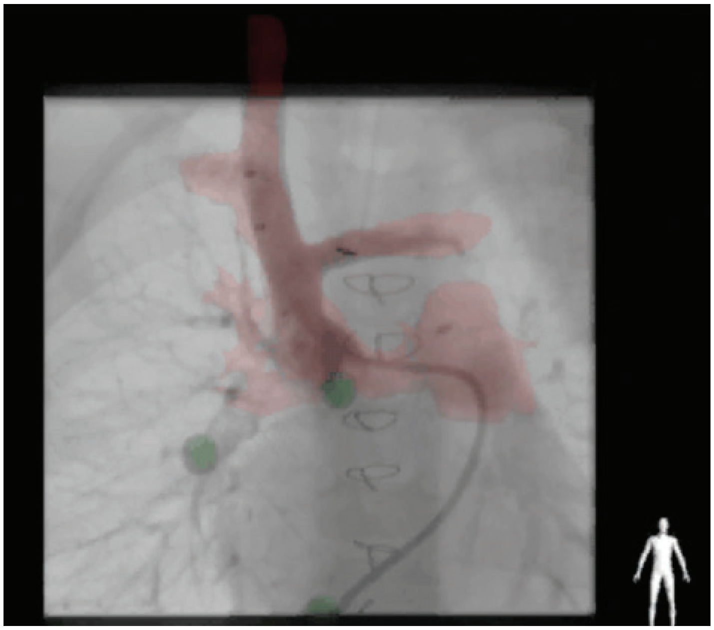

Figure 7. Computed tomography roadmap image over live fluoroscopy (red) used to guide balloon dilation of a stenotic right ventricle to pulmonary artery conduit.

3D Transesophageal Echocardiography Registration

In patients with CHD, real-time 3D transesophageal echocardiography (RT3D TEE) is routinely used during cardiac catheterization to visualize the soft tissue anatomy of the heart, which cannot be defined clearly by fluoroscopy. Images obtained by 3D TEE have been traditionally interpreted by the interventionalist with help from the echocardiographer and mentally "registered" to the fluoroscopic images. With the marked variety and complexity of catheter-based interventions in CHD, there is increased collaboration between the interventionalists and imaging cardiologists. In particular, the advent of percutaneous aortic valve replacement and device defect closures comes with new requirements from intraprocedure imaging and image guidance. Thus EchoNavigator (Philips Healthcare) registers RT3D TEE images with fluoroscopy, producing a 3D TEE roadmap. EchoNavigator offers several benefits, including improved understanding of anatomical structures imaged by TEE acquisition during the procedure, quick understanding of the spatial relation between the X-ray and ultrasound images, improved communication between the operators of the ultrasound and X-ray images, ability of the interventionalist to manipulate the 3D TEE images, and improved confidence when positioning the interventional device and guiding interventional procedures.

EchoNavigator uses image analysis to automatically find and track the position of the head of the TEE probe in three dimensions (Figure 8). During fluoroscopy, the silhouette of the head of the 3D TEE probe is used to determine its position in space and the direction of the 3D TEE imaging cone. This results in a 3D TEE image that dynamically reregisters in real time as the TEE probe is moved. The registered 3D image allows for visualization of intracardiac structures, guidance of catheter manipulation, and placement of devices in real time. As with all of the 3D image registration technologies, the 3D TEE images automatically track the fluoroscopic C-arm movements (Figure 9). Using EchoNavigator, multiple echocardiographic views can be displayed simultaneously. One view is controlled tableside by the interventionalist, who then has the ability to rotate, zoom, segment, and crop this 3D volume set. Additionally, the soft tissue anatomy seen by TEE in EchoNavigator can be marked. Because the spatial relationships of both images are harmonized by EchoNavigator, the new marks placed on the TEE images will be displayed in the corresponding X-ray location. These marks then serve as targets to direct catheter manipulations (Figure 10).

Advantages of EchoNavigator

Secundum Atrial Septal Defect Closure

The collaboration between the imaging cardiologist and the interventionalist is critical in atrial septal defect (ASD) and patent foramen ovale device placement. Using EchoNavigator, the defect size and catheter course can easily be visualized (Figure 8). Catheter manipulation becomes more straightforward for the interventionalist, enhancing confidence in the orientation of catheters and devices in relation to the ASD and in turn making the procedure more efficacious and efficient. With difficult or multifenestrated anatomy, target markers can be used to direct

Figure 8. EchoNavigator is an automated and intuitive link between fluoroscope and echocardiographic image orientation. (A) EchoNavigator's fluoroscopic view used to guide catheter placement across the atrial septum. EchoNavigator automatically recognizes the position and orientation of the head of the transesophageal echocardiography (TEE) probe (white outline on head of probe). Note: the current system colors the probe head green. The location of the ultrasound cone used to create the 3-dimensional (3D) images is displayed on the fluoroscopic image (purple outline). (B) EchoNavigator's 3D TEE image, which is spatially and temporally registered with the fluoroscopic image, used to guide transseptal catheter manipulation across the atrial septum (red oval in A and B).

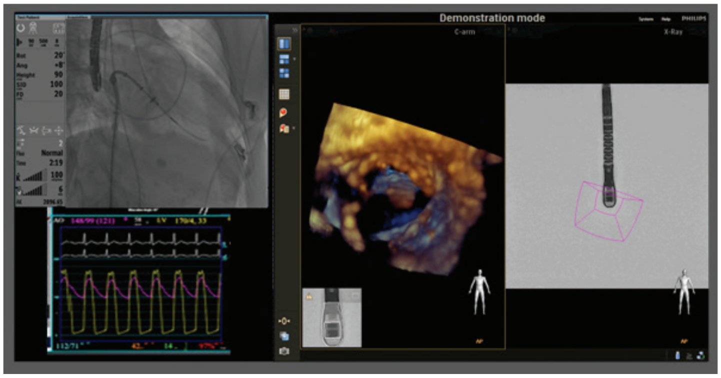

Figure 9. EchoNavigator images used to guide a mitral valve intervention. The transesophageal echocardiography (TEE) probe is positioned to view the mitral valve (left panel). By moving the C-arm gantry to a projection looking directly at the head of the TEE probe (right panel labeled X-Ray), the EchoNavigator 3-dimensional TEE image displayed in the C-arm view (center panel labeled C-arm) follows the gantry movement to give an en face view of the mitral valve.

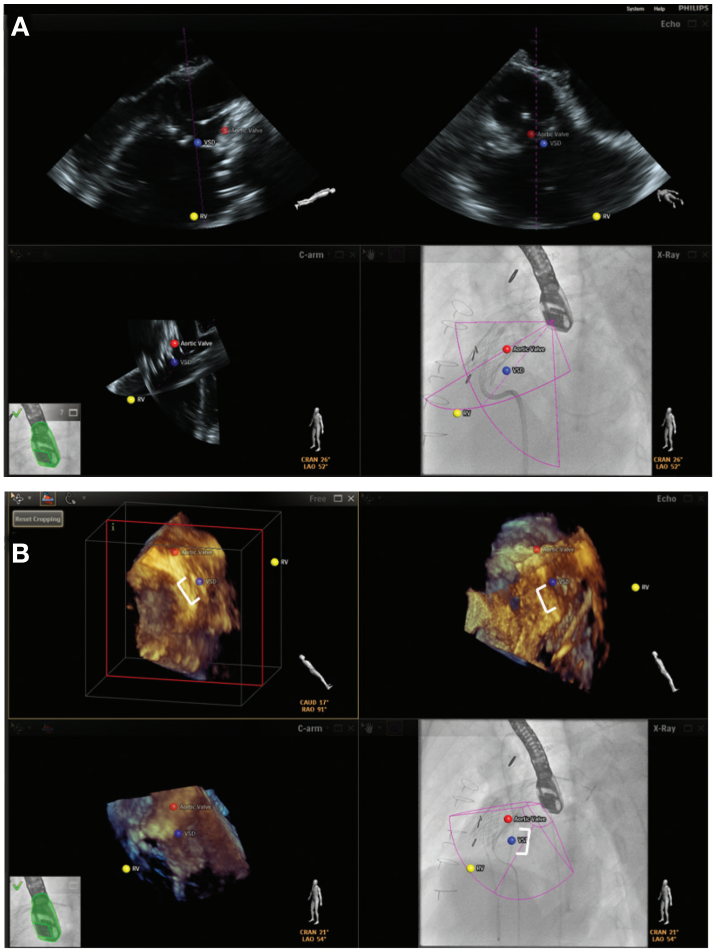

Figure 10. EchoNavigator images used to guide a device closure of a fenestrated surgical ventricular septal defect (VSD) patch. (A) Using orthogonal transesophageal echocardiographic (TEE) images (X-plane) (top panel labeled Echo), targets can be placed on anatomy of interest. Automatically, the targets are displayed in the corresponding anatomic position on live fluoroscopy (bottom right panel labeled X-Ray). (B) Targets are then used to direct catheter manipulations to facilitate the procedure. The VSD target was used to direct catheter cannulation of the fenestrated VSD patch (bracket in panels labeled Free, Echo, and X-Ray). VSD: fenestration in VSD patch; Aortic Valve: level of aortic valve annulus.

catheter access through a specific defect. Using the rotation and cropping features, the relationship of the closure device and the intra-atrial anatomy can be more fully assessed prior to and after device release.

Ventricular Septal Defect Closure

Device closure of muscular ventricular septal defects (VSD) and or a fenestrated VSD patch can be quite challenging. As with fenestrated ASDs, targets can be placed on both image sets to guide catheter access into the most appropriate defect for closure. Again, the device configuration and relationship to other cardiac structures (e.g., aortic valve) can be clearly visualized (Figure 10).

Fontan Fenestration and Baffle Leak Closure

Fontan fenestration closure is typically straightforward, except the relationship of the closure device and atrial anatomy/surgical fenestration can be more clearly visualized using EchoNavigator techniques. Leaks in the suture lines of Mustard and Senning baffles and in lateral tunnel Fontan baffles can be much more challenging to demonstrate by standard 2D echo imaging, and 3D TEE imaging may be a major adjunct to facilitate closure.[20] As such, the additional features of EchoNavigator such as C-arm follow and target placement may make baffle leak closures even more facile.

Atrial Septostomy or Fontan Fenestration Creation

The creation of an ASD may be necessary in patients with severe pulmonary hypertension to augment left ventricular preload and cardiac output. In these cases, 3D TEE provides an en face view of the atrial septum and other soft tissue anatomy. The EchoNavigator can be used to put a marker on the 3D TEE images, indicating where the atrial septum can be crossed safely. The marker will show up on the corresponding fluoroscopic images, allowing the interventionalist to perform a transseptal puncture in the most appropriate location in the septum to perform static balloon dilation or a blade catheter. The same technique can be applied for patients who require Fontan fenestration creation, such as those with protein-losing enteropathy or plastic bronchitis. While the guidance of the puncture into the atrium can be accomplished, clear real-time 3D visualization of fenestration stent positioning and deployment may be extremely beneficial.

Percutaneous Valve Interventions

Though EchoNavigator technology is relatively new, its beneficial role as a guide for complex valvular interventions such as mitral valvuloplasty, mitral valve clips, and prosthetic paravalvular leak closure is becoming realized by our adult structural heart interventionalists. The initial experience using this technology to guide transcatheter aortic valve implants is currently being gained, although its use for congenital valvular heart disease has been limited. However, EchoNavigator was used to help guide transcatheter valve implant into a bioprosthetic valve in the tricuspid position. Visualization of the bioprosthetic valve leaflets and their location was very clear and used to position the transcatheter valve on the leaflets of the prosthetic valve (Figure 11). EchoNavigator guidance will be most beneficial in situations where there is a very large bioprosthetic valve, and stable transcatheter valve placement may rely solely on the degenerated leaflets.

Challenges for 3D Multimodality Image Integration in CHD

Although RA can be useful for visualizing intracardiac structures, cardiac and respiratory motion hinders creation of MPR and 3DRA images (Figure 12). Thus, these modalities are used primarily for vascular structures. Metal objects from prior interventions can also produce significant artifact in MPR and 3DRA imaging (Figure 13). Though there is limited data suggesting RA does not expose the patient to radiation doses above standard cineangiography, further investigations are ongoing.[9, 11, 17]
One major limitation of using 3DRA, CT, and MRI images for fluoroscopic roadmaps is that these images are not acquired in real time, thus any change in patient position or distortion of the anatomy by ridged interventional equipment can cause misalignment of the registration (Figure 14). Static 3DRA, CT, and MRI models also do not account for cardiac and respiratory motion. There are reports in the literature, however, of nonrigid registration techniques that compensate for respiratory and cardiac motion, which may improve these modalities in the future.[21, 22] The major limitation to using 3D TEE registration is the large size of the TEE probes currently available. These probes can be placed safely only in children whose weight is greater than 25 kg; thus, continued development of small 3D TEE probes is essential.

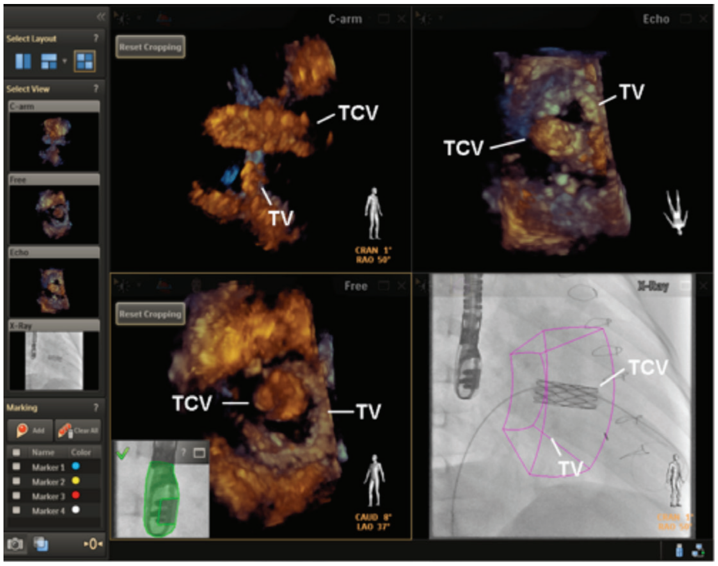

Figure 11. EchoNavigator images used to guide a transcatheter valve (TCV) implantation in a bio-prosthetic tricuspid valve (TV). Multiple views of the 3D TEE image are displayed simultaneously (panels C-arm, Echo and Free). Live fluoroscopy (panel labeled X-Ray) shows the partially deployed TCV where the metallic ring of the TV is only faintly visualized. The corresponding 3D TEE follow C-arm view (panel labeled C-arm) visualizes the soft tissue of the TV leaflets for improved confidence in positioning the TCV.

Future Directions

The work done in patients with CHD has relied primarily on more rapid cineangiographic acquisition protocols (3DRA) that are designed for more densely opaque structures (e.g., contrast-filled vessels). Other protocols, which obtain images more slowly, are available and are designed for better visualization of soft tissue structures including the myocardium ("C-arm CT"). These protocols have been applied to interventions[17] and may have a role in CHD. Additionally, gating of image acquisition may help optimize image quality.

Summary

Multimodality 3D image integration is being used more frequently for cardiac catheterization procedures in patients with CHD. Compared to standard fluoroscopy, these new imaging technologies are rapidly being reported as having greater diagnostic utility and improved procedural guidance. There are, however, clear limitations to the use of 3D image integration with fluoroscopy in CHD, and solutions to these limitations are actively being investigated. As these technologies advance, we are confident

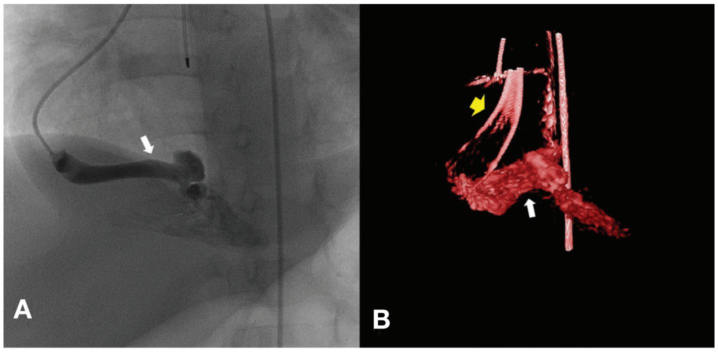

Figure 12. Images from a balloon occlusion selective right coronary artery (RCA) rotational angiography (RA) in a patient with RCA-right ventricular (RV) fistula. (A) Still-frame image from the RA showing the aneurysmal RCA (arrow) with fistulous connection to the RV. RA has become our procedure of choice for anatomic definition of coronary artery (CA) fistula. (B) 3-dimensional RA from the same RA: translation of the heart obfuscates definition of the CA and fistula (arrow) even though the RA is superb. The coronary catheter is also blurred secondary to cardiac motion.

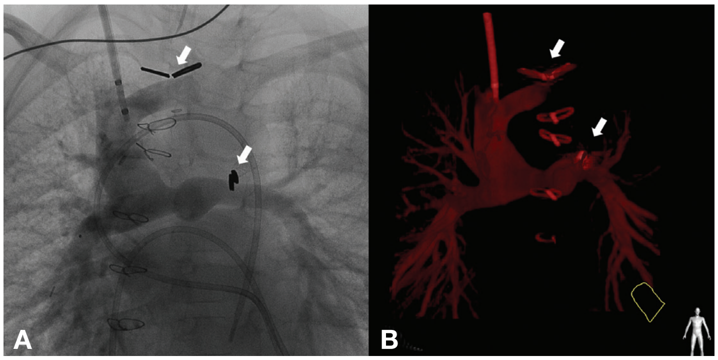

Figure 13. Images from a rotational angiography (RA) of the superior vena cava in a patient with a surgical cavopulmonary anastomosis (Glenn shunt). (A) Large, surgically placed metal clips (arrows) in the fluoroscopic field of view. (B) 3-dimensional RA from the same RA: note the significant metal artifact produced from the surgical clips (arrows) that obscure the distal aspect of the left pulmonary artery.

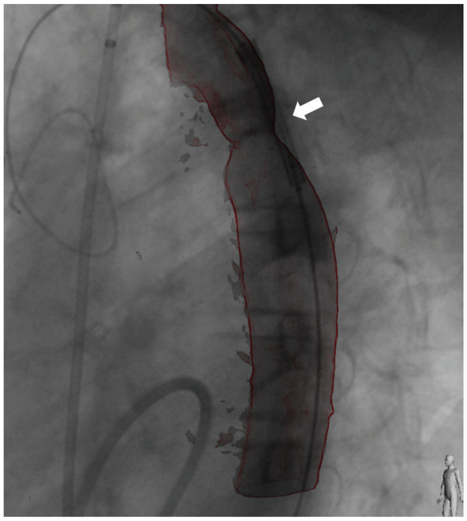

Figure 14. 3-dimensional rotational angiography (3DRA) roadmap (red) used to guide coarctation stent placement. The 3D images were obtained prior to placement of the stiff interventional; the wire and stent delivery system displaced the aorta rendering the overlay misaligned (arrow).

that multimodality 3D image integration will become a standard adjunct to cardiac catheterization for patients with congenital heart disease.

Conflict of Interest Disclosure: Dr. Bracken is employed full-time by Philips Research North America, and Drs. Fagan and Salcedo consult for Philips Healthcare.

Funding/Support: Dr. Bracken receives his salary from Philips Research North America for research activities at Children's Hospital Colorado, and Dr. Fagan receives research funding from Philips Healthcare.

Keywords: congenital heart disease, structural heart disease, rotational angiography, 3-dimensional rotational angiography, 3DRA, MRI roadmap, CT roadmap, 3-dimensional transesophageal echocardiography, 3D TEE, HeartNavigator, EchoNavigator

References

1. Thron A, Voigt K. Rotational cerebral angiography: procedure and value. AJNR Am J Neuroradiol. 1983 May-Jun;4(3):289-91.
2. Soderman M, Babic D, Homan R, Andersson T. 3D roadmap in neuroangiography: technique and clinical interest. Neuroradiology. 2005 Oct;47(10):735-40.
3. Berger MO, Anxionnat R, Kerrien E, Picard L, Söderman M. A methodology for validating a 3D imaging modality for brain AVM delineation: Application to 3DRA. Comput Med Imaging Graph. 2008 Oct;32(7):544-53.
4. Krishnaswamy A, Tuzcu EM, Kapadia SR. Three-dimensional computed tomography in the cardiac catheterization laboratory. Catheter Cardiovasc Interv. 2011 May 1;77(6):860-5.
5. Dori Y, Sarmiento M, Glatz AC, Gillespie MJ, Jones VM, Harris MA, et al. X-ray magnetic resonance fusion to internal markers and utility in congenital heart disease catheterization. Circ Cardiovasc Imaging. 2011 Jul;4(4):415-24.
6. Glöckler M, Halbfaß J, Koch A, Achenbach S, Dittrich S. Multimodality 3D-roadmap for cardiovascular interventions in congenital heart disease—a single-center, retrospective analysis of 78 cases. Catheter Cardiovasc Interv. 2013 Sep 1;82(3): 436-42.
7. Aldoss O, Darst J, Fonseca B, Truong U, Fagan T. Diagnostic utility of 3-dimensional rotational angiography in pediatric cardiac catheterization. Catheter Cardiovasc Interv. 2013 May;81(6):180.
8. Knecht S, Skali H, O'Neill MD, Wright M, Matsuo S, Chaudhry GM, et al. Computed tomography-fluoroscopy overlay evaluation during catheter ablation of left atrial arrhythmia. Europace. 2008 Aug;10(8):931-8.
9. Glatz AC, Zhu X, Gillespie MJ, Hanna BD, Rome JJ. Use of angiographic CT imaging in the cardiac catheterization laboratory for congenital heart disease. JACC Cardiovasc Imaging. 2010 Nov;3(11):1149-57.
10. Fagan T, Neubauer A, Einch S, Gaines K, Darst J. 3-dimensional rotational angiographic roadmapping used to guide congenital cardiac interventions. Catheter Cardiovasc Interv. 2011;78:S190.
11. Reinke G, Halbfaß J, Dittrich S, Banckwitz R, Köhler C, Achenbach S, et al. Three-dimensional rotational angiography in congenital heart disease: Estimation of radiation exposure. Open Journal of Radiology. 2013;3:124-29
12. Sra J, Narayan G, Krum D, Malloy A, Cooley R, Bhatia A, et al. Computed tomography-fluoroscopy image integration-guided catheter ablation of atrial fibrillation. J Cardiovasc Electrophysiol. 2007 Apr;18(4):409-14.
13. Maddux JT, Wink O, Messenger JC, Groves BM, Liao R, Strzelczyk J, et al. Randomized study of the safety and clinical utility of rotational angiography versus standard angiography in the diagnosis of coronary artery disease. Catheter Cardiovasc Interv. 2004 Jun;62(2):167-74.
14. Berman DP, Khan DM, Gutierrez Y, Zahn EM. The use of three-dimensional rotational angiography to assess the pulmonary circulation following cavo-pulmonary connection in patients with single ventricle. Catheter Cardiovasc Interv. 2012 Nov 15;80(6):922-30.
15. Glöckler M, Koch A, Halbfaß J, Greim V, Rüffer A, Cesnjevar R, et al. Assessment of cavopulmonary connections by advanced imaging: value of flat-detector computed tomography. Cardiol Young. 2013 Feb;23(1):18-26.
16. Fagan T, Kay J, Carroll J, Neubauer A. 3-D guidance of complex pulmonary artery stent placement using reconstructed rotational angiography with live overlay. Catheter Cardiovasc Interv. 2012 Feb;79(3):414-21.
17. Schwartz JG, Neubauer AM, Fagan TE, Noordhoek NJ, Grass M, Carroll JD. Potential role of three-dimensional rotational angiography and C-arm CT for valvular repair and implantation. Int J Cardiovasc Imaging. 2011 Dec;27(8):1205-22.
18. Gutierrez LF, Silva R, Ozturk C, Sonmez M, Stine AM, Raval AN, et al. Technology preview: X-ray fused with magnetic resonance during invasive cardiovascular procedures. Catheter Cardiovasc Interv. 2007 Nov 15;70(6):773-82.
19. George AK, Sonmez M, Lederman RJ, Faranesh AZ. Robust automatic rigid registration of MRI and X-ray using external fiducial markers for XFM-guided interventional procedures. Med Phys. 2011 Jan;38(1):125-41.
20. Klein AJ, Kim MS, Salcedo E, Fagan T, Kay J. The missing leak: a case report of a baffle-leak closure using real-time 3D transoesophageal guidance. Eur J Echocardiogr. 2009 May;10(3):464-7.
21. Faranesh AZ, Kellman P, Ratnayaka K, Lederman RJ. Integration of cardiac and respiratory motion into MRI roadmaps fused with x-ray. Med Phys. 2013 Mar;40(3):032302.
22. Timinger H, Krueger S, Borgert J, Grewer R. Motion compensation for interventional navigation on 3D static roadmaps based on an affine model and gating. Phys Med Biol. 2004 Mar 7;49(5):719-32.