REVIEW

Cardiac imaging of congenital heart diseases during interventional procedures continues to evolve: Pros and cons of the main techniques

Évolution de l'imagerie des cardiopathies congénitales en salle de cathétérisme : avantages et inconvénients des différentes techniques

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Abbreviations: 2D, two-dimensional; 3D, three-dimensional; ASD, atrial septal defect; CHD, congenital heart disease; CT, computed tomography; MRI, magnetic resonance imaging; TOE, transoesophageal echocardiography; TTE, transthoracic echocardiography; VSD, ventricular septal defect.

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Introduction

Cardiac catheterization has contributed to the progress made in the management of patients with congenital heart disease (CHD). It is widely used to percutaneously close intracardiac shunts [1,2], to relieve obstructive valvar or vessel lesions, and for transcatheter valve replacement [3–5]. Cardiac imaging has always been closely related to the development of cardiac catheterization. Catheterization became feasible under fluoroscopy [6]. It remains the cornerstone of cardiac imaging, but two-dimensional (2D) and three-dimensional (3D) echocardiography has become a complementary useful tool in the catheterization laboratory [7]. Fusion imaging between fluoroscopy and echocardiography or tomography further assist complex percutaneous procedures [8,9]. Multi-modalities imaging in the catheterization laboratory is thus nowadays available. In this comprehensive review, we provide an overview of conventional cardiac imaging tools used in catheterization laboratories in daily practice, as well as the effect of the recent evolution of and future imaging modalities. First, conventional fluoroscopy and its improvement are described. Then, the effect of multimodal echocardiography is discussed with regards to CHD current practice in the catheterization laboratory. Other 3D imaging techniques are further described, with their potential application in CHD. The focus is on the strengths and weaknesses of each imaging modality.

How the feasibility of cardiac catheterization was demonstrated

The first cardiac catheterization in man was demonstrated by X-ray imaging in 1929 [6]. At age 25, while receiving clinical instruction in surgery, Werner Forssmann (1904–1979) passed a urethral catheter through one of his left antecubital veins until its tip entered the right atrium. He then walked to the radiology department where an X-ray was taken [6]. Together with Courmand and Richards, he obtained the Nobel Prize in 1956. During his Nobel lecture, Courmand stated elegantly that cardiac catheterization was the ‘key in the lock’ to summarize its effect on the diagnosis and treatment of heart diseases. In the 1950s, dynamic images of heart cavities were feasible through the development of cineangiograms on roll films and image intensifiers.
Percutaneous treatments, such as pulmonary valvar stenosis dilation (1953) and balloon atrial septostomy (1966) then became feasible under fluoroscopy guidance [10,11].

**Fluoroscopy: the cornerstone of interventional catheterization**

Temporal resolution and image cadence with fluoroscopy are very high. The frame rate in routine practice is adjusted between 10 and 30 images per second to limit irradiation. Fluoroscopy allows a user-friendly real-time cardiac imaging. The radio-opacity of medical devices, wires and delivery sheaths is high, facilitating interventional procedures. Excellent temporal resolution ensures ‘eyes–hands’ synchronization and ‘device–target area’ accurate positioning. Since the very beginning of cardiac catheterization, and still today, almost all diagnostic and interventional catheterization procedures are performed under fluoroscopy. Thus, according to most operators, fluoroscopy is the cornerstone of catheterization and no other cardiac imaging technique is absolutely necessary (Table 1).

**Improvement in fluoroscopy imaging**

Digital subtraction angiography

Digital subtraction angiography is a fluoroscopy technique used to enhance blood vessel visualization. Contrast injection is delayed by around 2 seconds after the beginning of image acquisition. The frame rate is adjusted to 4–6 images per second. Final images are produced by subtracting the pre-contrast image (‘the mask’) from later images. Digital subtraction angiography is useful in CHD catheterization [12], for example to delineate aorto-pulmonary collaterals in Tetralogy of Fallot with pulmonary atresia, arterio-venous fistula and coronary fistula (Fig. 1, Video 1).

**Mono versus biplane tube**

Some CHD catheterization laboratories rely on a single X-ray tube, whereas the value of biplane tube is advocated in other centres and recommendations [13]. Biplane orthogonal imaging is recommended to ensure the accuracy of target lesion description. Nevertheless, all diagnostic and interventional catheterization procedures are feasible using a single mobile tube. Dual tube imaging allows faster biplane imaging during the same contrast injection. Thus, in some long procedures, such as pulmonary valve replacement, it may decrease the amount of injected contrast and help prevent contrast-induced nephropathy. Today, however, with the availability of low-osmolar iodine contrast, this is no longer a critical issue in paediatric cardiology, but it may be more relevant in adult CHD. Dual tube imaging is particularly useful in procedures involving the great vessels. It allows biplane imaging without moving the tubes or the examination table. Reference images are available for the interventionist, with anatomical markers such as bones without position changes, facilitating device or balloon positioning. Dual tube imaging may theoretically increase fluoroscopy time, but attention is taken by the operator to use simultaneous dual tube imaging in selected cases. Furthermore, in single X-ray tube imaging, the fluoroscopy time may be increased by tube position movement and image adjustment when multiple working incidences are necessary. Furthermore, with improvements in tube technology, the results of a recent study demonstrated that biplane imaging with flat-panel detectors produced less irradiation than a conventional system equipped with an image intensifier [14].

Spatial relationship may also be investigated through rotational angiography [15]. A dynamic angiogram is recorded during a semi-rotation of the X-ray tube (Video 2). However, it remains a 2D-imaging technique with the same limitations. Furthermore, it does not provide easily comprehensive video sequences and irradiation is increased. Thus, it remains little used in clinical practice.

**Limits of fluoroscopy**

Strength and weaknesses of fluoroscopy are displayed in Table 2.

**Irradiation: the Achilles heel**

Short-term deterministic effects of ionizing radiation are directly proportional to the dose received and result from irradiation at high doses. These complications are very rare, since effective doses usually range from only 2 to 12 mSv for the most frequent procedures [16]. However, concerns have been raised regarding stochastic effects of low doses that can appear later, randomly, such as cancer in patients, but also in operators [17]. Children are more susceptible than adults to the effects of ionizing radiation. Thus the primary radiation safety principle is to avoid irradiation when a non-ionizing imaging technique is alternatively available. Nevertheless, evolving technology with new-generation X-ray tubes, flat-panel detectors and decreasing irradiation algorithms have significantly decreased X-ray tube irradiation with comparable image quality [14].

**Imaging limits**

Fluoroscopy by itself does not allow visualization of smooth cardiac and vessel tissues — only calcified lesions are seen. Together with iodine contrast injection, a good visualization of cardiac cavities and vessels is provided. Proximal pulmonary artery and aortic lesions are well described. However, intracardiac shunts such as atrial septal defect (ASD) and ventricular septal defect (VSD) remain poorly visualized.

Furthermore, fluoroscopy provides only 2D images. Close structures such as distal pulmonary vessels may be superimposed; and valvar annulus and vessel diameters may not be accurately measured. If the projection is not perfectly aligned with the target vessels, foreshortening may lead to an underestimation of the length of the lesion. Multiple images are therefore needed to obtain a comprehensive spatial assessment.

**2D and 3D echocardiography**

Echocardiography provides real-time images without irradiation, and temporal resolution is excellent. Nowadays, echocardiography is a multi-modality tool. Moving quickly from one option to another, the echographer can display real-time 2D images facilitating device positioning,
### Table 1 Use of cardiac imaging modalities during catheterization of CHD.

<table>
<thead>
<tr>
<th>ASD closure</th>
<th>VSD closure</th>
<th>PDA closure</th>
<th>Pulmonary valvuloplasty</th>
<th>Aortic valvuloplasty</th>
<th>Foetal aortic valvuloplasty</th>
<th>Mitral valvuloplasty</th>
<th>Aortic (re)coarctation stenting</th>
<th>Pulmonary artery angioplasty</th>
<th>Pulmonary valve replacement</th>
<th>Tricuspid valve replacement</th>
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<tbody>
<tr>
<td>+++: Feasible without in some teams [26]</td>
<td>+++: Sufficient in some teams [33]</td>
<td>–: Only used in echo-guided closure in premature</td>
<td>–: Useful but not essential</td>
<td>–: Only used in echo-guided closure in premature</td>
<td>+++: Used by some teams in complex cases but not essential [21]</td>
<td>–: Used by some teams in complex cases but not essential [21]</td>
<td>–: Interest remains to be demonstrated</td>
<td>–: Interest remains to be demonstrated</td>
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<td>++: Sufficient in most teams [33]</td>
<td>++: Sufficient in most teams [33]</td>
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**Notes:**
- +++: Imaging technique used currently and essential for procedural success, interest well demonstrated.
- ++: Imaging technique used currently but not essential, interest demonstrated.
- +: Imaging technique used by some teams but interest less well demonstrated.
- ?: Imaging technique utility remains to be demonstrated.
- --: Imaging technique not useful.
- 2D: Two-dimensional.
- 3D: Three-dimensional.
- ASD: Atrial septal defect.
- CHD: Congenital heart disease.
- CT: Computed tomography.
- DSA: Digital subtraction angiography.
- ICE: Intracardiac echocardiography.
- TOE: Transoesophageal echocardiography.
- TTE: Transthoracic echocardiography.
- VSD: Ventricular septal defect.
**Table 2** Strength and weaknesses of imaging modality during catheterization of CHD.

<table>
<thead>
<tr>
<th></th>
<th>Fluoroscopy</th>
<th>Echocardiography</th>
<th>Echonavigator&lt;sup&gt;®&lt;/sup&gt; 3D-CT roadmapping</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional</td>
<td>DSA</td>
<td>TTE</td>
</tr>
<tr>
<td><strong>Minimum number of operators</strong></td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Ease of use</strong></td>
<td>+++</td>
<td>++</td>
<td>+++</td>
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<tr>
<td><strong>Imaging cadency</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td><strong>Real-time</strong></td>
<td>No</td>
<td>No</td>
<td></td>
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<tr>
<td><strong>3D</strong></td>
<td>+++</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td><strong>Irradiation</strong></td>
<td>Yes</td>
<td>Yes&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Yes</td>
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<tr>
<td><strong>Medical device visualization</strong></td>
<td>+++</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td><strong>Wires visualization</strong></td>
<td>Requires iodine contrast</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td><strong>Target lesion visualization</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Side effects</strong></td>
<td>Irradiation</td>
<td>None</td>
<td>Oesophageal perforation</td>
</tr>
</tbody>
</table>

+++: very good/high; ++: quite good/high; +: less good/high; —: bad/low; 2D: two-dimensional; 3D: three-dimensional; CHD: congenital heart disease; CT: computed tomography; DSA: digital subtraction angiography; ICE: intracardiac echocardiography; TOE: transoesophageal echocardiography; TTE: transthoracic echocardiography.

<sup>a</sup> In children >18—20 kg.

<sup>b</sup> Depending on procedure type.
show 3D volume-rendering images to better delineate the anatomical features of intracardiac lesions and explore the 3D dataset multiplanar reconstruction to provide accurate measures (Fig. 2). There is now much literature displaying the superiority of 3D over 2D echocardiography alone, in the catheterization laboratory [2,18].

Strength and weaknesses of various echocardiographic modalities are displayed in Table 2.

**Transthoracic versus transoesophageal echocardiography**

Transthoracic echocardiography (TTE) is the pivotal cardiac imaging tool for CHD management. A complete anatomical assessment is always performed by TTE before and after cardiac catheterization. In the catheterization laboratory, TTE is sometimes used during intracardiac shunting closure procedures such as ASD and VSD. TTE and fluoroscopy are not used concomitantly, given that the echo probe and the echographer’s hand will appear on the X-ray field. Transoesophageal echocardiography (TOE) may help to overcome this issue. The intra-oesophageal probe is thin and does not disturb the fluoroscopy guidance. It allows a real-time guidance of intracardiac shunt closure nicely displaying the device, the ASD or the VSD, and the surrounding structures.

New miniaturized intra-oesophageal probes allow its use in small children and even in neonates [19]. However, 3D technology is currently only available in adult probes, which have been used safely in children weighing at least 18–20 kg [2]. The main issue of TOE is that it requires deep sedation and often orotracheal intubation for patient comfort. Some argue that cardiac catheterization in paediatric cardiology is always performed under sedation. However, in our experience, a smooth sedation without orotracheal intubation is sufficient in most cases. In children, ASD closure can safely be performed under local anaesthesia and TTE guidance (unpublished data), whereas in our experience, for patient comfort, TOE requires sedation and orotracheal intubation. Moreover, in some procedures, such as complex ASD closure, visualization of the inferior rim is sometimes difficult, and complementary TTE may be required. A second rare but major issue is the risk of intra-oesophageal lesions. Intra-oesophageal perforation has occasionally been described in adults as well as children. Thirdly, the close relationship between the echographer and the X-ray tube results in echographer irradiation and particular attention should be paid by the operator to limit fluoroscopy.

Finally, whereas catheterization and TTE can be performed alternately by the same operator, real-time guidance by TOE requires a second echographer. The efficacy of the procedure relies on the experience of both operators and a trustworthy relationship, but ultimately the responsibility of the procedure is endorsed by the interventionist. This ‘judge and adviser situation’ has been widely explored in
psycho-sociology literature. The interventional cardiologist needs to communicate effectively with the echocardiographer in the catheterization laboratory to obtain the appropriate projections that will guide his manipulations. On the other hand, the echocardiographer has to be familiar with all steps of the procedure and the particular preferences and needs of the interventionist. Furthermore, the echocardiographer has to be patient since some procedures, such as para-valvular leakages or VSD closure, can be long. Thus, echocardiography in the catheterization laboratory appears to be a particular subspecialty of CHD echocardiography and specific training should be promoted.

Intracardiac echocardiography

Intracardiac echocardiography is now available with color Doppler, 2D and 3D technology. It requires a second venous femoral approach (8 or 10 Fr). It has been safely and accurately used to accomplish ASD closure and percutaneous pulmonary valve implantation [20,21]. A learning curve is necessary to understand how to manipulate, by rotation, the intracardiac probe positioned in the right atrium. Then, intracardiac echocardiography can be used by the interventionist alone, close to the femoral access. The major limitation is the high cost of the single-use probe.

Echocardiography and fluoroscopy fusion imaging

One of the main issues in cardiac imaging for percutaneous treatment of CHD is the inability to simultaneously visualize the anatomy, the catheter and the devices using a single imaging modality. When multiple imaging modalities are used in the catheterization laboratory, they are usually presented to the operator in separate screens and the operator has to fuse the displayed pictures mentally. A recent improvement by cardiac imaging industrialists has been to add the strength of each imaging modality into so-called fusion imaging. To be accurate, this integrated approach requires a real-time co-registration of both imaging modalities. Furthermore, the real-time merged image orientation must be appropriate to guide the intervention.

Echonavigator®

Echonavigator® (Philips Healthcare, Best, the Netherlands) is a software tool that enables real-time image synchronization and fusion of 2D and 3D-TOE with fluoroscopy images. The system places the two imaging modalities in the same coordinate system and is based on the localization and tracking of the TOE probe. After synchronization of TOE and
fluoroscopy images, the system automatically tracks and follows the movements of the C-arm gantry. When the C-arm is moved, echocardiography images are updated and reconstructed with the same orientation. On a large flat screen, four views are displayed simultaneously to the operators in real-time (Fig. 3). The first release of the software also allowed the placement of markers, in real-time, on specific points of interest on the echocardiography images that were automatically displayed on the fluoroscopy images (Fig. 4). In the second release of the software, real-time 3D echocardiography images can be merged and displayed with the fluoroscopy image (Fig. 3). The safety and feasibility of this novel technology have been demonstrated in adult structural heart diseases (MitraClip interventions and left atrial appendage closure) [8,22]. This software tool seems interesting to facilitate complex percutaneous procedure and decrease procedure length as well as radiation dose. However, there is currently no data to support these aspirations. In a first comparative study using the MitraClip procedure, with or without Echonavigator®, the total radiation dose and procedure time were not significantly different [8]. However, this study was biased by a learning curve effect and a selection bias given more complex procedures in the Echonavigator® group. Nevertheless, Echonavigator®
software requires a 3D-TOE probe that can only be used in patients weighing 20–25 kg. Thus, this technology is not currently available in small children.

Echo-guided catheterization without fluoroscopy

Echo-guided Rashkind procedures performed in the delivery room or in the neonatal intensive care unit provide evidence that some catheterizations can be performed safely without the need for fluoroscopy [23]. In these cases, the reason was the emergency indication rather than the radioprotection principle. However, given the risks related to irradiation in children [24,25], some teams have developed heart catheterization without fluoroscopy.

Percutaneous ASD closure can be performed under echocardiographic guidance alone without irradiation in carefully selected cases [26]. However, echocardiography is of limited value to follow wires and catheters within the heart or to assess the position of the wire distally in the left superior pulmonary vein. Thus, most operators still rely on fluoroscopy to check wire and device positions. In experienced hands, this procedure is fast, requiring only a few minutes of fluoroscopy [27]; the danger of this irradiation dose remains to be demonstrated.

Persistent ductus arteriosus closure is performed in routine practice under fluoroscopy guidance only [1]. In preterm neonates, percutaneous closure using new devices has been developed in some centers as an alternative to surgical ligation [28]. Echocardiographic guidance alone seems efficient and the better imaging option in experienced hands. Contrast injection should be avoided given the renal fragility and the hydro-electrolytical disorders in this particular indication [28].

Examples of procedures with echocardiography guidance: intracardiac shunt closure

Use of echocardiography in CHD interventional catheterization is displayed in Table 1.

Atrial septal defect

Percutaneous closure of ostium secundum ASD is the treatment of choice in most cases [29]. The procedure is performed under fluoroscopy and echocardiography guidance. Echocardiography is useful during the procedure to assess the morphology, number and sizes of the ASD. However, it is essential to check the good positioning of the device and the relationship with surrounding structures before device release. TOE was used in the pivotal trial of the Amplatzer septal occluder, and continues to be the most common ultrasound technology used for definitive ASD assessment, device selection and device guidance during implantation [30,31].

While 2D-TOE was successfully used in earlier studies, 3D-TOE appears to be more accurate for the assessment of ASD size and morphology [2] (Fig. 5).

The Zoom-3D-real-time mode is particularly interesting to display an en-face view of the ASD from the right or left side, making the ASD shape visually available for the interventionist. X-plane mode allows a 2D view and measurement of the ASD diameter according to two orthogonal planes. A single-beat full-volume pyramidal dataset of 60 × 30° with imaging cadency up to 25 Hz allows a multiplanar reformatting navigation to measure the maximal and minimal diameters and the area of the ASD. However, operators must be aware of potential artefacts such as stitching artefacts, dropout artefacts, blurring artefacts, blooming artefacts and rail-road shaped artefacts [32].

Nevertheless, practices still vary widely according to operator, experience and centre. In various studies, ASD closure has been safely performed under 2D- and 3D-TOE, 2D-TTE and 2D-ICE [2,20,33]. According to the Marie-Lannelongue Hospital experience, when balloon sizing is used, 2D-TTE appears as efficient as 2D-TOE in children (unpublished data). On the other hand, according to Necker Hospital experience, 2D-TOE may be sufficient to perform ASD closure without the need for balloon calibration, decreasing fluoroscopy time to a minimum of 30 seconds [27]. In Toulouse children’s hospital, 3D-TOE is used in current practice and the effect of Echonavigator® in ASD closure (Figs. 3 and 4) is under investigation.

Ventricular septal defects

Percutaneous closure of VSD remains controversial. When this procedure is performed in carefully selected cases, percutaneous closure of muscular or membranous VSD is guided by fluoroscopy and echocardiography. Echocardiography, particularly in 3D mode, is essential to assess VSD morphology and size and thus device choice (Fig. 6).

In most cases, an arterio-venous loop is performed and the device is partially deployed in the aorta and then gently pulled back across the aortic valve in the left ventricle and positioned across the VSD. TOE is useful during this procedure to follow the course of the device and its relation to the aortic valve. The device position and its relationship with surrounding structures are assessed before release by TOE or TTE.

Effect of echocardiography guidance in aortic valvuloplasty

Percutaneous balloon valvuloplasty is the first-line treatment in many centers for the management of valvar aortic stenosis in neonates and children [34–36]. The procedure is performed under fluoroscopy and is successful in about 75% of cases [35]. The main issue is the risk of aortic regurgitation; therefore, some centers still consider surgery as the method of choice. The risk of aortic regurgitation is increased in the case of previous aortic regurgitation and is related to the balloon/aortic annulus diameter ratio [37]. Aortic regurgitation may occur with an oversized balloon, whereas residual stenosis may occur with an undersized balloon. The accurate measurement of the aortic annulus is essential. Aortic annulus can be measured on angiographic images, but several studies have demonstrated that accurate annulus geometry and measurements, as well as better procedure results, are obtained using echocardiographic guidance, particularly with the 3D mode [18,38,39]. Even in critical neonatal aortic stenosis, TOE guidance is feasible using a micro-TOE probe [19].
Figure 5. Transcatheter valve replacement with 3D-CT Roadmapping. The angulation of the X-ray system is optimized using the fused image. Coronary arteries can be localized on the fused image (black arrow: right coronary artery; white arrow: left coronary artery) before (A) and after (B) aortography. C and D. The Melody valve was then implanted (white arrows) with good scaffolding of the aneurism developed on the distal suture of the homograft (black arrows).

Figure 6. Double atrial septal defect (ASD) closure under 3D echocardiography. A. En-face view of the atrial septum. Two distant ASDs of approximately the same size are observed as well as the rims. View of the first closure device from the (B) left and (C) right sides. A guidewire was introduced into the second defect (D: right view; E: left view). F. Left en-face view of the two devices after closure. ASD: atrial septal defect.
**Other 3D imaging modalities**

**3D computed tomography Roadmapping**

3D image data sets obtained from rotational angiography, cardiac magnetic resonance imaging (MRI) and computed tomography (CT) scans can be integrated with fluoroscopy. First, a pre-procedural 3D image volume data set is acquired. Then, a 3D reconstruction and segmentation of the structure of interest is performed. Finally, a 3D reconstructed model is integrated to fluoroscopy during the catheterization procedure. Thus, image fusion could improve the 2D spatial visualization of images from a medical examination by merging the 3D model with conventional interventional X-ray images. CT is the method of choice for pre-procedural 3D image acquisition given its high image resolution of both the vasculature and the airway, facilitating segmentation. This imaging technique has been previously developed in interventional neuro-radiology [40–43], abdominal and vascular interventional radiology [44–47] and cardiology for electro-anatomical mapping during atrial fibrillation ablation procedures [48–51].

3D-Roadmapping has emerged as a promising modality applicable for the catheterization of complex CHD [9,52–54]. Various points of interest of this integration method have been suggested. First, due to the full 3D registration between the CT volume and the X-ray system, the rotation of the CT volume is linked to the rotation of the X-ray system, allowing one to assess the best position for the X-ray system to face the anomaly without the need to do any X-ray. Thus, irradiation may be decreased by this technique [9]. Second, during the procedure, image fusion allows for good positioning of catheters, guides and balloons or devices, without injection of contrast. Third, because it is possible to add specific thoracic structures to the 3D model, it improves the visualization of anatomical structures that surround the target lesion. Thus, it could reduce the need for angiographies looking for their localization before interventional catheterization. For example, aortography to localize the coronary tree before transcatheter pulmonary valve replacement is not mandatory because coronary arteries can be localized on image fusion (Fig. 7).

One major limitation of 3D rotational angiography, CT or MRI for fluoroscopic roadmaps is that these images are not acquired in real-time. Changes in patient position and distortion of the target lesion by the catheter or guidewires can induce misalignment of the registration. Furthermore, 3D fused models are static and do not follow cardiac and respiratory motion. These limits further explain why this technique is primarily used for vascular lesions rather than intracardiac shunts. Finally, a pre-procedural CT scan is required, thus increasing ionizing irradiation. However, a CT scan is often available from the routine screening of complex CHD. Thus, the objective of 3D-Roadmapping is to optimize the use of CT scans. This has been done initially for diagnostic purposes and can also be a helpful tool during the interventional procedure to decrease ionizing radiation.

Aortic (re)coarctation stenting is usually performed under fluoroscopy alone in most centers. Some groups suggest that fusion imaging may be useful to facilitate device positioning with reduced fluoroscopy time [9]. For example,
**Figure 8.** Aortic coarctation stenting with 3D-CT Roadmapping. Endovascular treatment of a 38-year-old woman with Roadmapping. A and B. The aortic isthmus was much narrowed (and endovascular repair was performed using image fusion). B. First, image fusion allowed the C-arm to be placed for the optimal view of the aortic isthmus, without X-ray exposure. Once positioned, a catheter was placed into the supra-isthmic aorta via femoral access. C. Catheter positioning was controlled on the fused image (without injection of contrast agents). D. Stent positioning and angiography was performed just before stent delivery. E. Angioplasty with implantation of a covered stent (CP Stent™ Numed Hopkinton, NY, USA) was performed F. with a good final result.

**Fig. 8** shows the case of a 38-year-old woman with aortic coarctation stenting using Roadmapping.

Pulmonary artery dilation and stenting remains a long and complex procedure, which is performed under fluoroscopy alone in most cases, though Roadmapping is used by some operators. Pre-acquired 3D images using CT or rotational angiography are merged with live fluoroscopy images. In these cases, the 3D images are segmented and reconstructed at the beginning of the intervention and are then superimposed on the fluoroscopy image. This real-time
Figure 9. Pulmonary stenosis stenting with 3D-CT Roadmapping. In case of pulmonary artery stenosis, the optimal position to correctly expose the narrowed segment is sometimes difficult to define. A. In this example of left pulmonary artery stenosis, the CT scan-derived image fusion allowed, without any more X-ray exposure, to place the X-ray system in the optimal position to see the stenosis (white arrow), while (B) exposing perfectly pulmonary bifurcation and lobar pulmonary artery. Angiography is performed at the beginning of the procedure to check the accuracy of the fused image. The rest of the procedure was performed without angiography until stent delivery and final inspection.

A multi-modality approach allows virtual planning of stent or valve implantation by 3D visualization of the pulmonary artery tract. The fluoroscopy incidence that is the best to guide the procedure can be determined using the fusion image without the need for complementary angiography. Stent positioning would be facilitated. However, it remains little used for live guidance as CT-derived Roadmap images are static and not synchronized to respiratory motion or position changes. Figs. 7 and 9 show examples of pulmonary artery stenosis stenting and transcatheter pulmonary valve replacement using Roadmapping.

MRI-guided catheterization

Some teams have developed MRI-guided catheterization, though many issues had to be overcome [55]. First, real-time MRI was developed, combining acquisition, reconstruction and display with low latency (<250 ms). In real-time MRI, the imaging matrix, and thus spatial resolution, is reduced in size to support an imaging speed of 5–10 frames per second. Second, both haemodynamic and electrocardiographic monitoring equipment had to be adapted. Third, a specific MRI catheter without a heating phenomenon had to be developed. These catheters are ‘passive’ or ‘active’ depending on whether they are visualized based on intrinsic material properties or based on signals from embedded receiver coils and electronics. However, recent studies in adults have suggested that some procedures, such as MRI-guided right heart catheterization, can be performed safely and successfully in approximately the same amount of time as a classical X-ray-guided procedure [56]. Furthermore, following therapeutic procedures such as a percutaneous closure of septal defects or aortic coarctation stenting in animals [56–58], MRI-only guided pulmonary valvuloplasty procedures have recently been performed [59]. These works begin translation of cardiovascular interventional MRI into clinical practice. Besides the lack of irradiation, MRI provides superb tissue visualization as well as blood flow. However, the logistical complexity, a reduced temporal and spatial resolution, and the limited range of suitable catheters and devices still limit its use.

3D printing

Ex-vivo modelling and visualization of intracardiac anatomy of CHD is now feasible using 3D printing [60,61]. Printing has been used by surgeons to prepare and check the feasibility of complex cardiac surgeries, such as double-outlet right ventricle intra-ventricular repair [60–62]. There is a wide spectrum of potential applications for the percutaneous treatment of CHD. For example, modelling of the right ventricular outflow tract could be used to check the feasibility of percutaneous pulmonary valve replacement [3,21,60]. Rather than doing per-procedural ASD balloon sizing, we could imagine that the device could be selected and tested based on an ex-vivo ASD model. In the same way, device type and size choice might be easier for complex muscular VSD closure. Modelling could also be used for a simulation-based training programme [63]. However, before 3D printing can be used in current practice, many technical concerns have to be overcome, with regards to feasibility, cost and accuracy.

Conclusions

Cardiac imaging has greatly contributed to advances in the catheterization of CHD. Practices vary widely by operator and centre. Fluoroscopy remains the cornerstone technique and continuous efforts are undertaken to decrease the associated irradiation. 2D and 3D echocardiography have become complementary useful tools, particularly during intracardiac shunt closure. Fusion imaging, between CT or echocardiography and fluoroscopy, further extends the armamentarium of cardiac imaging modalities in the catheterization laboratory and its effect is under investigation.
Disclosure of interest

CHU Toulouse has received grants from Phillips Healthcare to develop 3D imaging of congenital heart diseases.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.acvd.2015.11.011.

References


