Three-Dimensional Rotational Angiography

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Konstantin von Aspern and Lukas Lehmkuhl

27.1 Introduction

Due to the complex nature of vascular pathologies, accurate anatomical understanding of a target vessel in relation to surrounding structures is crucial for treatment planning and execution [1]. Since images produced through routine two-dimensional fluoroscopy may provide an incomplete geometrical representation of cardiovascular structures [2], new three-dimensional imaging techniques were developed to overcome these limitations. Three-dimensional rotational angiography (3D-RA) produces cross-sectional images comparable to computed tomography (CT), which can be used for further 3D reconstruction and could help to overcome these limitations. Rotational angiography is an X-ray-based imaging technique using a C-arm-mounted flat-panel detector to generate fluoroscopic images from multiple angles around the patient. It is also known as flat-panel CT or cone-beam CT. Its versatility makes it an attractive modality applicable also intraprocedurally in a multidisciplinary setting [3].

K. von Aspern
Department of Cardiac Surgery, University Heart Center Leipzig, Leipzig, Germany

L. Lehmkuhl (✉)
Clinic for Radiology, Cardiovascular Center Bad Neustadt, Bad Neustadt, Germany
e-mail: lukas.lehmkuhl@helios-kliniken.de; lukas.lehmkuhl@radiologie-bad-neustadt.de

27.2 Technical Aspects

So far a variety of different products using 3D-RA and their respective reconstruction software are commercially available, such as the syngo DynaCT™ (Siemens), Innova CT HD™ (GE Healthcare), INFX+CT™ (Toshiba), XperCT™ (Philips), and Safire 3D-C™ (Shimadzu).

Image acquisition by 3D-RA is performed using intra-arterial contrast agent application in most clinical scenarios. A set of digital images is acquired at equiangular intervals along a circular arc of the C-arm around a fixed reference point (isocenter). The raw data provides cross-sectional submillimeter images consisting of isotropic voxels. These voxels are the basis for further multiplanar or three-dimensional reconstruction. Each image slice has comparable features to CT images but with different resolution properties (Fig. 27.1). Usually 3D-RA focuses on angiographic imaging with strong delineation of the contrast medium but a reduced visualization of low-contrast tissue and calcified structures due to the susceptibility to X-ray scatter of area detectors and cone-beam geometry and different settings of tube voltage and current. Various strategies are employed to optimize the reduced low-contrast visibility including anti-scatter grids, air gaps, wedge-shaped beam compensating filters, and software corrections [2].

O. H. Stanger et al. (eds.), *Surgical Management of Aortic Pathology*,
https://doi.org/10.1007/978-3-7091-4874-7_27

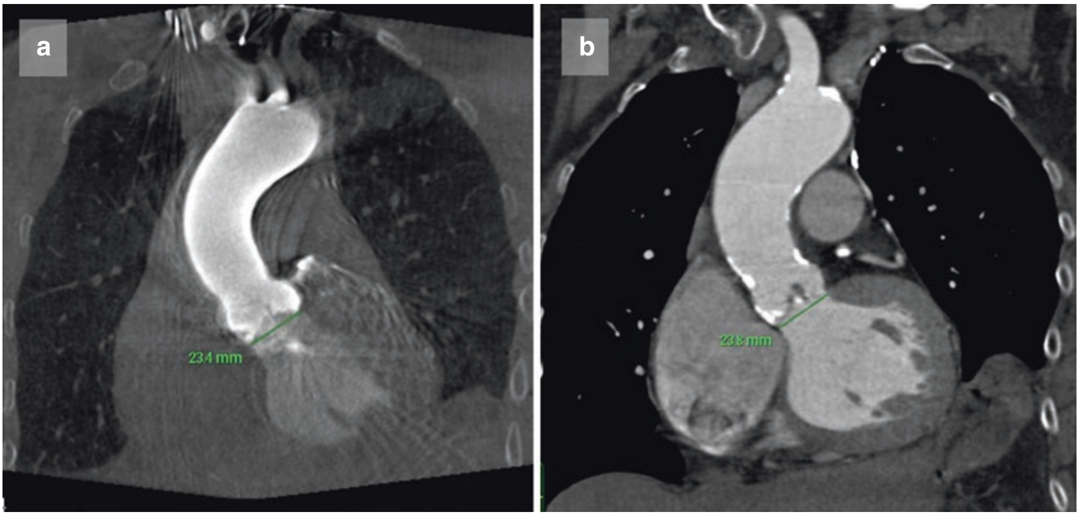

Fig. 27.1 Coronal multiplanar image reconstruction of the aortic root and ascending aorta in the same patient with severe aortic stenosis. (**a**) 3D-RA with 20 mL diluted contrast medium administration via pigtail catheter in the ascending aorta. (**b**) CT with intravenous administration of 70 mL non-diluted contrast agent. Note the different visualizations of adjacent structures (left ventricle, right atrium, pulmonary artery) and of aortic and coronary artery calcification

The amount and dilution ratio of contrast medium, the overall numbers of projections, and the tube current necessary to generate satisfactory image quality vary considerably depending on the area of interest and planned procedure.

Typically a bolus of diluted contrast medium is administered via a catheter positioned in the vicinity of the area of interest and followed by a 180°–240° circular rotation of the C-arm at 30–60 degrees per second. Raw data is then transferred onto a dedicated 3D workstation equipped with reconstruction software.

While standard angiographic equipment is available in most interventional centers, not every system and protocol is equally suitable for all possible applications.

27.3 Clinical Application in Cardiac and Vascular Procedures

27.3.1 3D-RA in Transcatheter Aortic Valve Implantation (TAVI)

Transcatheter aortic valve implantation (TAVI) strongly depends on reliable imaging. Best knowledge of the individual anatomic morphology is crucial for accurate valve positioning and to avoid side effects such as severe paravalvular leakage, valve dislocation, coronary artery obstruction, annulus rupture, or aortic dissection [4]. The use of 3D-RA during TAVI focuses mainly on correct perpendicular angulation of the C-arm and correct positioning of the valve to avoid repetitive contrast medium application through online overlay of reconstructed images [4, 5].

27.3.2 Procedural Protocol for TAVI

During 3D-RA for TAVI, the patient is placed with the arms to the side of the body. Typically a 6 Fr pigtail catheter for contrast medium application is positioned in the non-coronary cusp of the aortic root, and a balloon-tipped pacing catheter is placed into the right ventricle. Injection of diluted contrast medium (0.3–0.8 per kg diluted 1:2–3, flow rate 15–25 mL per second) followed by a 180°–220° circular rotation of the C-arm (1 s prescan delay) is performed. Alternatively, undiluted contrast agent at slower injection rates may be administered (e.g., 30 mL at 8 mL/s). Images are acquired during inspiratory breath-hold to reduce respiratory motion and subsequent artifacts. Immediately before and during contrast injection, rapid ventricular pacing (RVP) at 180–200 beats per minute is instituted. Image acquisition is completed within 5 s (60 frames/s, ≈70–125 kV), generating 240–320 projections. Depending on the reconstruction software abilities, the aortic valve cusps are automatically depicted, and a circle is generated at the nadir to indicate the aortic valve plane. A volume-rendered 3D model of the aortic root may be generated and used as an overlay to guide the procedure. Typically a simplified delineation of the aortic root is used as a real-time mask for perpendicular angulation. A suitable cusp alignment, favored by many interventionists, is where the non-coronary cusp appears on the left and the left coronary cusp on the right (Fig. 27.2).

27.3.3 Measurement Accuracy and Annulus Sizing

Apart from achieving the ideal C-arm angulation for prosthesis implantation, 3D-RA has also been used for measuring aortic structures, particularly the aortic valve annulus diameter and its distance to the coronary ostia [4–6]. Few studies have compared agreement and reproducibility of measurements obtained by 3D-RA with multislice computed tomography (MSCT). Results showed that measurements of supraannular structures—like the sinotubular or ascending aortic diameters—were without significant difference between both methods; however, measurements of the aortic annulus by 3D-RA differed significantly and were less reproducible in comparison with MSCT [4]. A reason contributing to this difference is the method of contrast application during 3D-RA via a catheter in the aortic sinus. With the contrast medium entirely situated above the aortic valve, adequate depiction of the left ventricular outflow tract is difficult, leading to a lack of visible reference points and subsequently vague bordering of the aortic annulus. Recently the method of left ventricular contrast injection has been investigated and found feasible with measurement accuracy and reliability in good agreement with MSCT [7].

Besides choosing a suitable prosthesis size—taking into account native annulus dimensions, shape, and adjacent calcification—the correct implantation angle and plane play a pivotal role for

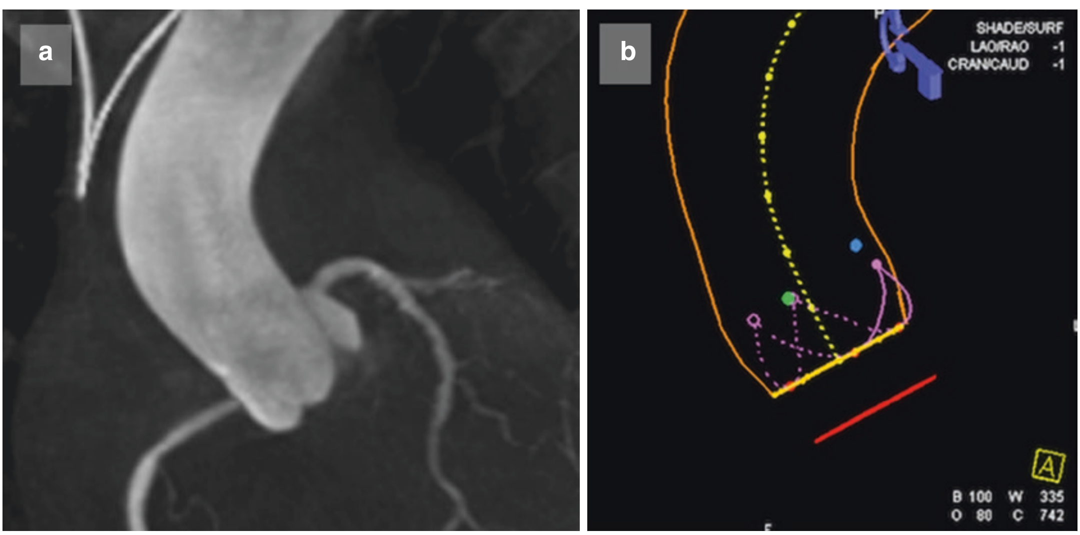

Fig. 27.2 (**a**) 3D-RA of the aortic root and ascending aorta (maximum intensity projection). (**b**) Software-based semiautomatic evaluation of the 3D-RA data in the same patient provides the aortic annulus size and its angulation prior to a TAVI procedure

a successful TAVI procedure. It has been shown that paravalvular leakage following TAVI is frequent and has a negative impact on survival [8, 9].

Utilization of 3D-RA in combination with additional add-on software, providing automatic root segmentation and anatomical landmark indication, has been found to be beneficial (Fig. 27.3). Analysis has shown that an excellent implant angle is significantly more likely to be achieved with the use of (semi)automatic reconstruction software. Furthermore, non-excellent implant angles were more often associated with postprocedural paravalvular leakage, concluding that optimizing implant angles may be important in reducing paravalvular leakage after TAVI [10, 11].

27.3.4 Practical Considerations and Limitations

Transcatheter aortic valve implantation has been shown to improve hospitalization rates and mortality in patients deemed inoperable [12]. Among others, an important aspect for a patients' eligibility for TAVI—and the decision whether to choose a retrograde or antegrade approach—is dependent on preoperative imaging to assess vascular anatomy, dimensions, and calcifications.

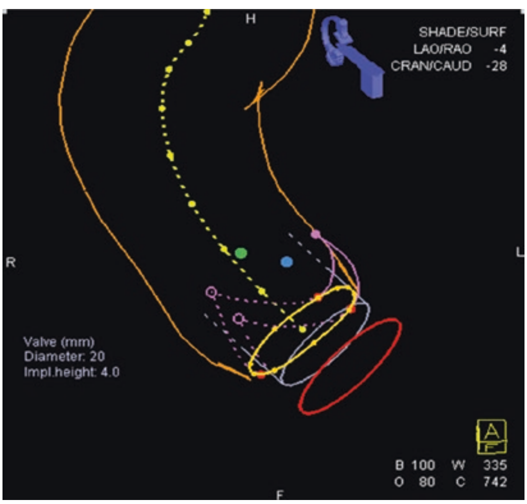

Fig. 27.3 Simulation of an aortic valve prosthesis implantation based on an individual 3D-RA dataset to ensure a correct prosthesis choice

In theory, provided that a modern interventional hybrid operating room is available, 3D-RA offers the advantage to intraprocedurally plan the arterial access site, perform aortic annulus sizing, and correct C-arm angulation and prosthesis implantation without the need for transferring the patient to a dedicated radiology unit. A recent study concluded that 3D-RA is equal to MSCT in accurately depicting the iliofemoral arterial caliber and tortuosity; however, it is inferior in the assessment of calcification [13]. A study examining feasibility and accuracy of 3D-RA in pretreatment evaluation of aortic aneurysms found that assessment of the iliac arteries was suboptimal due to a limited imaging volume size [14]. Regarding the abovementioned influence preoperative imaging has on patient selection prior to TAVI and the limitations this imaging modality poses, intraprocedural 3D-RA alone may not sufficiently answer all key questions necessary for decision-making.

When using 3D-RA during a standard TAVI procedure, radiation protection represents an issue. Usually scatter radiation coming from the bottom is shielded against by radiopaque covering at the side of the operating table. This protection, however, needs to be dismantled during circular image acquisition around the patient. After 3D-RA is performed, the covering needs to be reattached, which can pose tremendous difficulties, given that the operating field is already covered and sterile.

Another issue concerning 3D-RA image quality is associated with breathing motion of the non-intubated patient when in horizontal position. Although breath-hold image acquisition is preferred, most patients are not capable to comply due to respiratory distress caused by the underlying pathology.

Modern hybrid operating rooms have standard imaging equipment readily available, including C-arm-mounted flat-panel detectors for angiography and 3D-RA. Depending on the equipment used, detector panel sizes and ultimately the effective maximum field of view (FOV) vary considerably. A too small FOV may result in inadequate depiction of the entire heart and the ascending aorta and should be considered when planning a hybrid OR.

27.4 3D-RA in Endovascular Aneurysm Repair (EVAR)

Accurate assessment of anatomical structures is mandatory for successful planning and execution of endovascular aneurysm repair (EVAR). To date multislice computed tomography (MSCT) is the preferred imaging modality and emerged as the gold standard prior to EVAR [15]. Only recently on-table 3D-RA has been used as an alternative and/or complementary to MSCT for EVAR of the abdominal aorta with promising initial results [14, 16].

Particularly in emergency EVAR due to ruptured aneurysms, periprocedural 3D-RA may avoid the diagnostic delay of pre-procedural MSCT, which needs to be performed outside the intervention lab or hybrid operating room.

In comparison to conventional open aortic aneurysm repair, EVAR is reported to be associated with an increased frequency of secondary interventions, mandating regular follow-up imaging [15]. It has been suggested that early re-interventions may be a reflection of inadequate detection and immediate treatment of intraprocedural complications [15]. Whether 3D-RA during EVAR has the potential to improve this issue is subject to ongoing research with promising initial results [15, 17, 18].

27.4.1 Procedural Protocol for EVAR

Depending on the extent and individual features of the aortic aneurysm and the respective center experience, 3D-RA protocols vary with regard to catheter placement, contrast medium, and detector configuration.

Typically a 4 Fr diagnostic catheter is introduced via a femoral artery and positioned at the level of or slightly above the renal arteries. Between 90 and 140 ml, diluted contrast medium (dilution ratio 1:1) is injected at 6–9 mL per second. After a prescan delay of 3–4 s, images are acquired during breath-hold. Within 6–8 s, a circular C-arm rotation of 180–220 degrees with 15–50 frames per second is performed, registering between 120 and 420 projections. These cross-sectional images are then sent to a dedicated workstation for reconstruction [17].The three-dimensional volumetric reconstructions can then be used as a roadmap overlay on live fluoroscopy and synchronized with C-arm and table positions to reduce repetitive contrast agent application and total radiation dose [17].

27.4.2 Feasibility and Accuracy

Choosing a suitable aortic stent graft as well as its correct positioning is an important aspect for successful EVAR. Absence of procedural complications such as endoleaks and graft kinking, verified by an uneventful follow-up CT, is associated with improved outcome [15].

Initial experience with 3D-RA during EVAR has shown that it provides sufficient information for determining the correct treatment and selecting the proper stent graft before EVAR [14]. It represents a feasible intraoperative adjunct to completion angiography, which improves intraoperative quality control during endovascular repair of abdominal aortic aneurysms.

To date MSCT represents the gold standard in planning EVAR as well as follow-up examination. Recently 3D-RA in conjunction with the completion angiogram has been trailed against early follow-up MSCT with regard to detection of procedural complications. In view of the results, it was suggested that 3D-RA, as a feasible imaging method both in EVAR planning and as completion imaging to detect complications missed by conventional angiography, could replace early follow-up MSCT, potentially reducing overall radiation and contrast use [15, 19]. It remains unclear whether the 3D-RA is sufficiently accurate for the detection of low-flow endoleaks compared to modern scanning protocols that allow a dynamic MSCT [20].

27.4.3 Limitations and Practical Improvements

Although initial experience using 3D-RA during EVAR is promising, certain practical limitations have been described. A major issue poses the limited FOV resulting from the detector panel size and orientation. Typically multiple roadmaps of the entire aorta and target vessels are needed for planning and execution [17]. The orthogonal orientation of the detector (horizontal mode) results in a further reduction of the effective FOV so that the stent graft usually is not completely included [15]. In order to tackle this issue, a group of researchers updated the 3D-RA software, switching from horizontal to vertical detector mode (90° rotation), thus being able to depict a larger portion of the region of interest [15].

Imaging artifacts due to scatter have also been described to be a limitation of 3D-RA. Typically radiopaque guide wires are used during the procedure. Exchanging these for regular catheters further reduces image artifacts and should be considered whenever possible prior to 3D-RA image acquisition.

27.5 Summary

Three-dimensional rotational angiography has evolved to be an additional valuable imaging tool to optimize procedural success also in endovascular treatment and cardiothoracic surgery. It can help to overcome the limitations of two-dimensional fluoroscopy and the hereby associated incomplete geometrical representation of cardiovascular structures. Its versatility makes it an attractive modality applicable intraprocedurally in a multidisciplinary setting. Despite a promising perspective for the 3D-RA, there are numerous limitations, particularly with regard to the size of the scan field and for reasons of practicality in a sterile environment.

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