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3D Printing in Medicine

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Virtual 3D reconstruction of complex congenital cardiac anatomy from 3D rotational angiography

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Abstract

Background Despite advancements in imaging technologies, including CT scans and MRI, these modalities may still fail to capture intricate details of congenital heart defects accurately. Virtual 3D models have revolutionized the field of pediatric interventional cardiology by providing clinicians with tangible representations of complex anatomical structures. We examined the feasibility and accuracy of utilizing an automated, Artificial Intelligence (AI) driven, cloud-based platform for virtual 3D visualization of complex congenital heart disease obtained from 3D rotational angiography DICOM images.

Methods Five patients selected at random with 3DRA performed in the pediatric cardiac catheterization suite were selected. 3DRA's were performed following published institutional protocols and segmentations performed by primary operators. The 3DRA DICOM images were anonymized as per protocol and exported. Images when then processed by Axial3D Artificial Intelligence (AI) driven cloud-based platform for virtual segmentation. Two separate expert operators were selected to subjectively analyze the segmentations and compare them to the operator reconstructions for anatomic accuracy.

Results Comparing results with local reconstructions by expert operators, five different patient anatomies were analyzed, showcasing Axial3D's ability to produce highly detailed reconstructions with improved visual appeal, including color-coded segments for implanted materials like stents. The reconstructions exhibited superior segmentation of different intrathoracic structures when compared to local models, offering valuable insights for medical professionals and patients.

Conclusions The use of the AI driven, cloud-based platform for 3D visualization of complex congenital heart lesions presents a promising advancement in pediatric interventional cardiology, facilitating enhanced patient care, procedural planning, and educational opportunities for trainees and patients alike.

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Background

Despite advancements in imaging technologies, including computed tomography (CT) scans and magnetic resonance imaging (MRI), these modalities may still fail to capture intricate details of congenital heart defects accurately. Virtual 3-dimensional (3D) models have revolutionized the field of pediatric interventional cardiology by providing clinicians with tangible representations of complex anatomical structures [1]. Studies have shown discrepancies between virtual 3D models and intraoperative findings, highlighting the challenge of achieving precise anatomical replication [2]. However, imitations of these reconstructions include the time and resources required for creating and utilizing virtual 3D models. The acquisition of images, segmentation, and subsequent model reconstruction is a time-intensive and laborious process, demanding specialized expertise and the use of advanced software necessitating proper training in the field.

Virtual 3D reconstructions are increasingly recognized as assets in pediatric interventional cardiology [3]. Conventionally, these reconstructions have been created from cross-sectional imaging modalities such as CT angiograms or MRIs. However, 3D rotational angiography (3DRA) has been increasingly used for 3D reconstructions using a variety of proprietary software available in the market. Additionally, live reconstructions while performing a complex catheterization often includes a second operator, or additional team members with advanced training to reconstruct. This poses a practical challenge in clinical settings where time is often limited. However, 3DRA DICOM images for virtual 3D model reconstruction through external services has not previously been reported.

We present a series of 5 patients who underwent cardiac catheterization with 3DRA DICOM images exported for external model reconstruction. We aimed to evaluate the feasibility and of virtual 3D model reconstruction from 3DRAs performed in patients with complex congenital heart disease using a commercially available service.

Methods

Five patients selected at random that had a 3DRA performed in the pediatric cardiac catheterization suite were selected. The selection was made in a retrospective fashion including only patients which had reconstructions already performed and 3DRA was done as part of the institutional standard of care in the last 12 months.

The 3DRAs were performed per published institutional protocols with contrast dilution and volumes dictated per patient weight. Simultaneous multi-site injections were performed when appropriate. The rotational angiogram was performed during cessation of respiration (expiratory breath hold) to eliminate motion artifact, no pacing was used in these cases for imaging acquisition. In our center, patients under 50-kg receive a diluted contrast solution (75% contrast/25% normal saline) while larger patients use straight contrast injections. The full volume injection is then given over a total of 5 s starting 1 s prior to the cameras' initial rotation. The C-arm AP-camera then rotates from extreme right posterior oblique (RPO) camera angle (posteriorly looking at the right scapula) starting position and performs a full 270-degree continuous spin [4]. The images were then processed and reconstructed on local software by the operator performing each procedure and stored.

The 3DRA DICOM images were anonymized as per protocol and exported. Images where then uploaded to and processed by Axial3D (Belfast, Ireland) Artificial Intelligence (AI) driven cloud-based platform for virtual segmentation. These images are then verified by a biomedical engineer for quality control based on provided patient demographics as per company workflow (not assessed in this study). Two separate expert operators, not included in the original local segmentation, were selected to subjectively analyze the segmentations and compare them to the original operator reconstructions for anatomic accuracy. No statistical analysis was performed.

Results

The case descriptions and patient demographics are summarized in Table 1. Patient pathologies included: 3 patients with single ventricle physiology status post each palliation stage (s/p Sano shunt, s/p bidirectional Glenn and s/p Fontan completion), patient with a ventricular septal defect status post pulmonary arterial band placement and a patient with coarctation of the aorta post-stent placement. Separate operators confirmed the anatomic accuracy of the models individually. The assessment of the images was done in a descriptive fashion with side to side comparisons of anatomical details and potential motion artifacts. Commentary included the more appealing visual appearance of the Axial3D reconstructions with color coding of airway, catheter placement and implanted material, such as stents, when available. The reconstructions exhibited superior segmentation of varying intrathoracic structures compared to local models given the limitations of the system's 3DRA workstation. Comparison of the models with the 2D angiography and the standard 3DRA reconstructions from the system can be seen in Fig. 1.

The average segmentation time of these images by the operators go from 10 to 30 min. The images turnaround time by Axial3D was 1 business day.

Table 1 Patient demographics, anatomy, and procedural details

Patient #	Age	Weight (kg)	Height (cm)	Gender	Diagnosis	Prev. Procedures	Procedure Performed	Total Injection Vol. (mL)	% Contrast/saline	Injection site (single vs. dual)
1	3 yrs	13.4	95	F	RAI, L-looped ventricles, DORV, bilateral SVC's, pulmonary atresia, right aortic arch, situs inverssus	left mBTT shunt followed by shunt takedown and bilateral Glenn anastomosis	Pre-Fontan Catheterization	20	70/30	RSVC/LSVC*
2	14 yrs	89.1	169.5	M	Coarctation of the Aorta	none	Coarctation stent placement of a 36 mm LD Max stent on a 18 mm balloon	90	100/0	Aorta
3	9 yrs	31.8	132	M	HLHS (MS/AA)	Norwood palliation with Sano modification, followed by right sided Glenn anastomosis, and eventual completion of a 18 mm fenestrated extracardiac Fontan and placement of a 10 mm Valeo stent in the LPA	Diagnostic catheterization and collateral embolization	45	70/30	SVC/IVC*
4	6 mo	5.1	57.5	M	mitral stenosis and BAV with stenosis and apex forming LV, VSD, hypoplastic arch, and unrestrictive atrial septum	Aortic arch reconstruction, coarctation repair, and pulmonary artery band placement	Pre-Glenn hemodynamic catheterization	10	70/30	Main PA
5	3 mo	6	63.5	M	HLHS (MS/AS)	Norwood palliation with Sano modification	Pre-Glenn hemodynamic catheterization	15	70/30	RV

*denotes dual simultaneous injection at different sites for rotational angiography

Right atrial isomerism (RAI), double outlet right ventricle (DORV), Superior Vena Cava (SVC), Hypoplastic Left heart Syndrome (HLHS), Mitral Stenosis (MS), Aortic Atresia (AA), Aortic Stenosis (AS), Bicuspid Aortic Valve (BAV), Left Ventricle (LV), Ventricular Septal Defect (VSD), Left Pulmonary Artery (LPA), Pulmonary Artery (PA), Right Ventricle (RV), modified Blalock-Thomas-Taussig shunt (mBTT shunt)

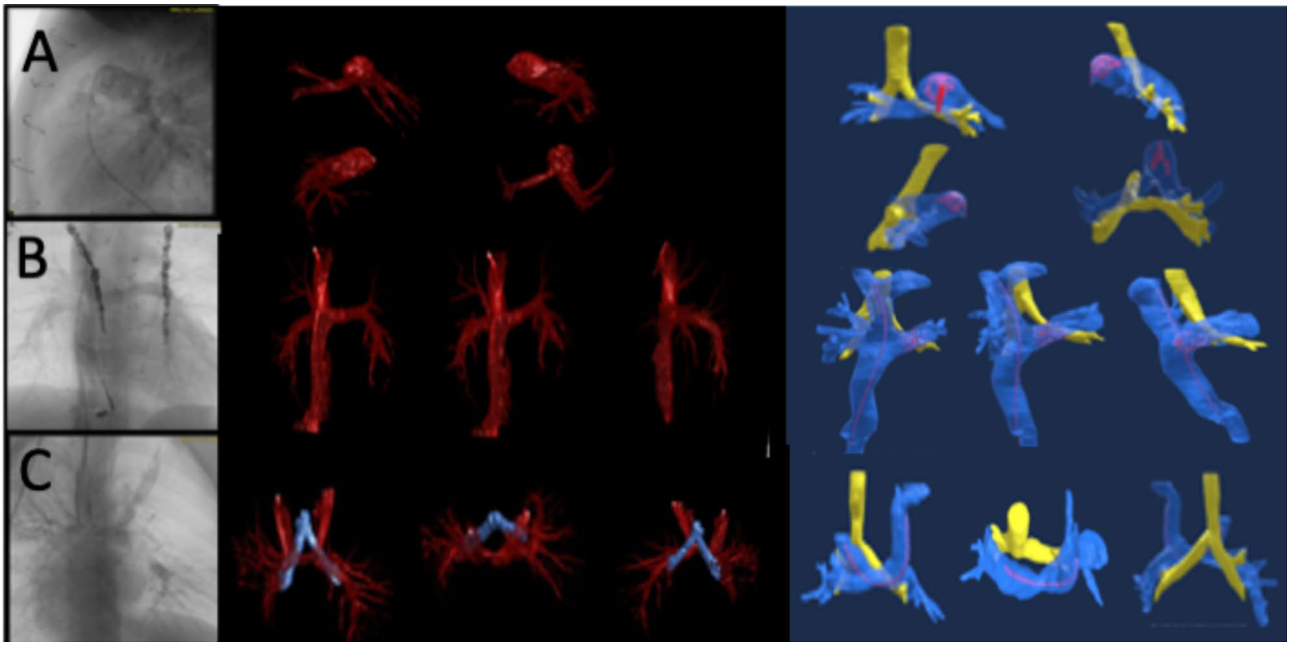

Fig. 1 Visual Comparison of Reconstructions from 3DRA Images. From left to right, compare the 3DRA injection with the operator reconstruction (black) compared to the exported reconstruction (blue). (**A**) Pulmonary arteries post-band placement. (**B**) Fontan completion with a left pulmonary artery stent (red dots). (**C**) Bilateral bidirectional Glenn anastomosis. In the exported reconstructions, the airway is delineated in yellow, catheter position in red, stent noted with red dots

Discussion

As multiple services and software platforms have emerged in recent years the options available for proceduralists to perform these reconstructions have been on the rise. However, the time spent on reconstructing these models from various imaging modalities is not insignificant for providers who are already stretched for time.

Traditionally, these models have been reconstructed from cross-sectional imaging modalities such as CT angiograms or MRIs [5, 7]. In contrast, 3DRA is performed in the catheterization suite by highly trained proceduralists. This is performed by placing angiographic catheters in the desired vasculature. Rapid pacing is commonly used in many centers but our center doesn't use it as affects the cardiac output and alters volumetric dimensions of the anatomy. These images are then processed by the institutions local software and is thus then processed and reconstructed by the proceduralists either for live guidance or for medical documentation. However, this approach is usually done by the same operator, or occasionally a second operator if needed for live guidance, performing the cardiac catheterization and can be time consuming in an already busy and time-constrained field. In addition, the appearance of the segmentation is limited to the different vendors' workstation capabilities. On average we estimate the time spent on reconstruction from 3DRA can range from 10 min to 30 min based on experience compared to the one business day of the Axial3D service turnaround time. However, the reconstructions are not always done same day or live depending on available time and critical nature of the imaging for the procedure. Furthermore, the use of other available software adds additional processing time including exporting of the DICOM images which then may be subject to each software's processing capabilities and further need for training in segmentation by each operator.

Though the use of 3D printing from 3DRA in congenital heart disease has been widely described for procedural planning and education, to our knowledge, the use of 3DRA DICOM images for virtual 3D model reconstruction using external services has not been previously described [4–9]. Reconstruction services provide multiple options of 3D modeling for healthcare professionals by not only providing virtual models for 3D visualization, 3D printing of hard models, as well as flexible/functional models for surgical planning and practice. However, traditionally these services require advanced imaging such as CT and MRI. The model reconstructions performed by Axial3D from the 3DRA images showed not only that this is a feasible modality for use, but also showed that 3DRA images are of comparable quality to CTA and MRI and include visually appealing details of the anatomy as well as implanted material such as stents. Additionally, a myriad of interventions are performed in the cardiac catheterization suite which can significantly change and improve the anatomy of each patient, and thus 3DRAs performed following these interventions can provide up-to-date anatomic insight to other practitioners, the patients, and their families. This is a significant advantage to the traditional in-suite software capabilities, and pre-procedural advanced imaging modalities, which can provide families and medical trainees with invaluable insight into these complex anatomic pathologies.

Conclusion

Reconstruction of 3DRAs in the catheterization suite is feasible, however time consuming with limited options in smaller centers. Furthermore, 3D printed models have become more widely available, however these add hours to processing and result time by the operator. We prove the feasibility of using commercially available services for 3D reconstruction of complex congenital heart disease with DICOM images exported from a 3DRA which has not been previously described. These virtual models provide not only anatomic accuracy but a higher degree of detail compared to local reconstruction especially following complex interventions. These models provide clinicians with further advanced imaging modalities to allow for creation of 3D models to aid in excellent patient care, procedural planning, and trainee and patient education.

Limitations

Given that this is a feasibility study, only 5 patients were included from images using Philips system. A larger study is needed to validate this technology and challenge real turnaround times using wider imaging vendors.

Abbreviations

CT	Computed tomography
MRI	Magnetic resonance imaging
3D	Three dimensional
3DRA	3D rotational angiography
AI	Artificial intelligence
s/p	Status–post
2D	Two dimensional
AP	Camera–anterior–posterior camera
Kg	Kilogram
RPO	Right posterior oblique

Author contributions

E.M. wrote the main manuscript text and developed all figures. S.S. conducted data collection and reviewed and edited the manuscript. J.Z. developed the concept, reviewed and edited the manuscript and fiugures. All authors reviewed and approved the manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Human ethics approval

Approved under Colorado Multiple Institutional Review Board 19-2892.

Consent to participate

Written informed consent for publication of their clinical details and/or clinical images was obtained from the parent/guardian of the patients. A copy of the consent form is available for review by the Editor of this journal.

Competing interests

Dr. Zablah is a medical advisor for Axial3D.

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