Utility of 3-D printing for cardiac resynchronization device implantation in congenital heart disease

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Introduction

Three-dimensional (3D) printing is increasingly being used to visualize relationships of anatomical structures and is becoming more popular in planning cardiac procedures.[1] 3D printing of the coronary sinus (CS) and its branches has not previously been described. The value of 3D models could be particularly high in the planning of cardiac resynchronization therapy (CRT) device implantation where procedural difficulty is anticipated. CRT implantation can be challenging in patients with congenital heart disease and other structural heart abnormalities where the anatomical relationships are complex. A precise 3D model can be beneficial for planning CRT implants to clarify essential anatomical details such as size of the right atrium, angulation of the CS take-off, and location of CS branches and their relationship to the systemic ventricle.

We describe the use of a 3D printed model to assist in CRT lead implantation in a case of congenitally corrected transposition of the great arteries (ccTGA). The accurate representation of the CS and its branches helped the operators preselect an appropriate target branch and specific equipment required.

Case report

A 76-year-old woman with ccTGA and a permanent pacemaker for complete heart block was referred for consideration for upgrade of her device to a cardiac resynchronization defibrillator. Her right ventricle (RV) functioned as the systemic ventricle and had deteriorated in function in the preceding few months to an ejection fraction of 30%–35%. Her functional status had also declined and was consistent with NYHA functional class 3. She experienced shortness of breath on minimal exertion. Her relevant medical history included atrial fibrillation, severe systemic atrioventricular valve dysfunction, severe biatrial enlargement, and hypertension. She had a single-chamber pacemaker implanted with a transvenous lead in the pulmonary ventricle for complete heart block 20 years prior with a ventricular pacing percentage of 90%. Following consideration and discussion with the patient and her family, a decision was made to implant a cardiac resynchronization defibrillator.

Difficulty with implanting the left ventricular lead was anticipated owing to the patient's congenital heart disease. Specifically, adequate lead position and appropriate choice of target CS branch for the systemic ventricular lead were important. Therefore, a preoperative cardiac computed tomography (CT) was performed using a GE Lightspeed VCT 64-slice CT Scanner (GE, Boston, MA) with 0.625 mm slice thickness (Figure 1). As per the standard protocol at our institution, 105 mL of iodinated contrast agent (Omnipaque-350, GE, Boston, MA) was injected, at a flow rate of 4.5 mL/s, via a needle in the antecubital vein followed by a 20 mL saline bolus chaser. Data acquisition was electrocardiogram-gated throughout examination and tube current was as per routine cardiac CT protocol.

A 3D mesh model was created to assist the operators in visualizing the 3D structure of the heart and the relationship of the coronary branches to the systemic ventricle. The CT Digital Imaging as Communication in Medicine (DICOM) files were imported into 3D Slicer version 4.10.2 (www.slicer.org). A region of interest was created around the heart. The heart model was segmented by using the semiautomated "grow from seeds" extension. Segmentation defects were corrected by modifying seeds and manual editing. The final model, including the CS, was made hollow with a shell thickness of 2 mm. The file was imported into Formlabs Preform software (Formlabs Inc, Somerville, MA). Layer thickness was set to 0.1 mm and the model was printed in gray resin (Figure 1).

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KEY TEACHING POINTS

- Clinical congestive heart failure due to systemic right ventricular failure is common in patients with congenitally corrected transposition of the great arteries (ccTGA). The benefit of cardiac resynchronization therapy (CRT) in ccTGA has been established in a few small studies.
- The complex anatomical relationships in the ccTGA population and other congenital heart diseases can result in challenges for CRT lead implantation.
- Cardiac computed tomography images can be used to reconstruct and print an accurate patient-specific 3-dimensional heart model in cases of congenital heart disease. The coronary sinus ostium and branches can be precisely represented to assist in CRT implant preoperative planning.

The 3D model of the patient's heart revealed a patent subclavian vein, a severely enlarged right atrium, and a large CS with no obstruction or angulation of the ostium. There was a single large lateral branch of the CS in addition to the middle cardiac vein. The lateral vein was identified as the target vein. It was possible to visualize on the model that the placement of a lead in this branch would provide a lateral position appropriate for resynchronization. The angle of this branch to the CS was approximately 130 degrees and therefore we predicted that a sub-selector at this angle would be needed during the case to engage this branch.

The operators examined the 3D model preoperatively. The procedure was performed as per the department's standard approach. The existing pacing lead was capped. A new defibrillator lead was placed in the pulmonary ventricle. A deflectable sheath (Attain 6227; Medtronic, Minneapolis, MN) was used to engage the CS. A CS venogram was performed, confirming 1 suitable target branch, which corresponded to the 3D model (Figure 1). A 130-degree sub-selector sheath (Attain Select; Medtronic) was used to advance an angioplasty wire into the target branch. A quadripolar lead (Attain Performa; Medtronic) was advanced over the wire into position. Pacing thresholds were suitable and this was determined to be an acceptable final lead position. The total procedure time was 2 hours and 7 minutes and fluoroscopy time was 9 minutes and 40 seconds.

Discussion

Three-dimensional imaging and printing has been used in preoperative planning in cardiac surgery as well other disciplines.[2] It has previously been used to clarify relationships of intracardiac structures and is becoming more popular in planning procedures in congenital heart disease owing to the complex spatial relationships.[1] As far as we are aware, this technique has not previously been used to plan CRT implantation. CRT implants have a failure rate of up to 10% in the general population.[3] There are no large studies assessing failure rate of CRT implant in congenital heart disease, but it is likely to be higher owing to the complex anatomy. Three-dimensional printing may be important in this population to help plan procedures.

Clinical congestive heart failure due to systemic right ventricular failure occurs in >30% of patients with ccTGA by the age of 45 years.[4] There has been a demonstrated association between pacemaker implantation and deterioration of systemic ventricular (RV) function and worsening systemic atrioventricular valve regurgitation in ccTGA.[5] The benefit of CRT in ccTGA has been established in a few small studies. One recent study reported on 53 patients with ccTGA who underwent pacemaker implantation.[6] There was a lower rate of worsening RV function on follow-up in patients who received biventricular pacing compared with those with univentricular pacing (21% vs 52%, $P = .043$). Of the patients (n = 53) that received univentricular pacing only, 26% were upgraded to biventricular pacemakers owing to

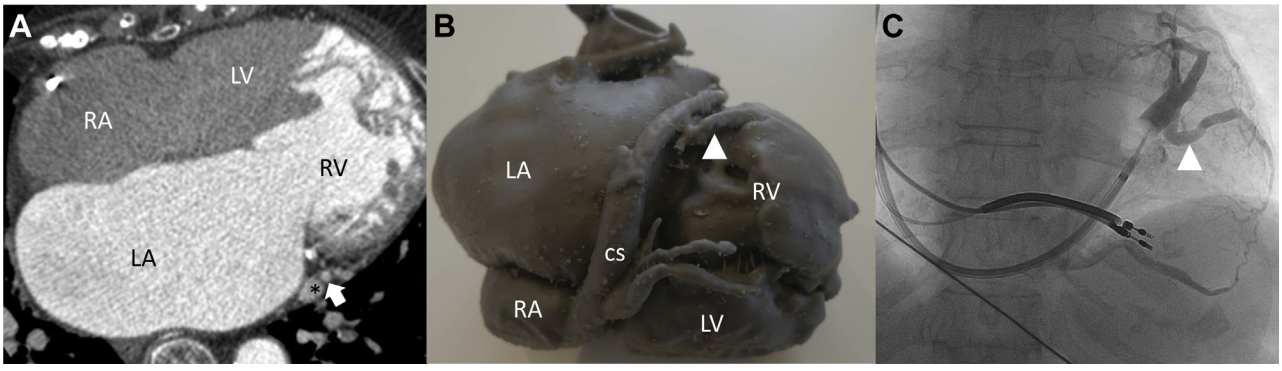

Figure 1 Three-dimensional (3D) printed model of congenitally corrected transposition of the great arteries for preoperative planning in cardiac resynchronization therapy (CRT) device implantation. **A:** Computed tomography imaging of the coronary sinus (CS). The arrow indicates the target branch of the CS. The asterisk indicates the main CS body. **B:** 3D printed model of the heart. The white arrowhead indicates the target branch. **C:** Venogram during CRT implant procedure. The white arrowhead indicates the target branch. LA = left atrium; LV = morphologic left ventricle; RA = right atrium; RV = morphologic right ventricle.

deteriorating systemic ventricular function. Half of these patients responded to this treatment with an improvement in ventricular function.

The anatomical variation in the ccTGA population can result in challenges for lead implantation. The CS has been shown to develop with the morphologic atria in ccTGA while the venous branches develop with the morphologic ventricles.[7] Therefore, the CS commonly drains into the right atrium. The venous branches, which would usually be targeted for placement of systemic right ventricular lead, are often small and short. A study examining 56 pathologic cardiac specimens from patients with ccTGA found the CS to have a predictable ostial location and anatomical course in 88% of cases.[7] The abnormalities of the CS observed in this study included atretic ostia, abnormal ostial location, or multiple ostia. In the patients with CS abnormalities, 70% had Thebesian veins with ostia $\geq$1 mm that could be considered an alternative option for access to the coronary venous system. There was also extensive collateralization between the RV and LV noted, which could make pacing the RV via the middle cardiac vein or anterior intraventricular vein possible.

In this case, we were able to obtain an accurate 3D model of the CS and its branches that correlated to the findings of intraoperative venogram. The 3D model allowed visualization of the region of the systemic ventricle that the lead would contact following placement in the target vein. Preoperative planning using the 3D model may have contributed to the shorter procedure duration, by providing knowledge of the CS branch anatomy and required equipment. Prior studies reported median procedure times in non–congenital heart disease patients to be approximately 170 minutes.[3] This technique can be used to help with preoperative planning in future cases of CRT implantation where procedural difficulty is anticipated and can help predetermine target branch for appropriate lead positioning.

Conclusion

We were able to use cardiac CT images to reconstruct and print an accurate patient-specific 3D heart model in a case of ccTGA. The CS ostium and branches were precisely represented to assist in CRT implant planning. The benefit conferred by the 3D model in this case was in preoperative determination of equipment required and selection of appropriate target branches of CS lead. The opportunity for the operators to study this model preoperatively may have also contributed to shorter fluoroscopy and procedure duration.

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