Artificial Organs

Translation of First North American 50 and 70 cc Total Artificial Heart Virtual and Clinical Implantations: Utility of 3D Computed Tomography to Test Fit Devices

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Abstract: Since the creation of SynCardia's 50 cc Total Artificial Hearts (TAHs), patients with irreversible biventricular failure now have two sizing options. Herein, a case series of three patients who have undergone successful 50 and 70 cc TAH implantation with complete closure of the chest cavity utilizing preoperative "virtual implantation" of different sized devices for surgical planning are presented. Computed tomography (CT) images were used for preoperative planning prior to TAH implantation. Three-dimensional (3D) reconstructions of preoperative chest CT images were generated and both 50 and 70 cc TAHs were virtually implanted into patients' thoracic cavities. During the simulation, the TAHs were projected over the native hearts in a similar position to the actual implantation, and the relationship between the devices and the atria, ventricles, chest wall, and diaphragm were assessed. The 3D reconstructed images and virtual modeling were used to simulate and determine for each patient if the 50 or 70 cc TAH would have a higher likelihood of successful implantation without complications. Subsequently, all three patients received clinical implants of the properly sized TAH based on virtual modeling, and their chest cavities were fully closed. This virtual implantation increases our confidence that the selected TAH will better fit within the thoracic cavity allowing for improved surgical outcome. Clinical implantation of the TAHs showed that our virtual modeling was an effective method for determining the correct fit and sizing of 50 and 70 cc TAHs. **Key Words:** Virtual implantation—3D surgical modeling—Total artificial heart—Computerized tomography—Magnetic resonance imaging.

Heart failure is the final common pathway of all cardiac diseases, accounting for nearly 250,000 deaths per year (1). With shortages in available donor hearts, mechanical circulatory support systems have emerged as life-saving augmentation of heart failure for bridge-to-decision, bridge-to-recovery, and bridge-to-transplantation or destination therapy (2–4). Patients with irreversible biventricular failure have two options: biventricular assist device (BIVAD) or temporary total artificial heart (TAH). However, the BIVAD system can be complex, involving multiple controllers and batteries, and still depends upon native ventricles (i.e., pharmaceutical support) and proper valvular function. On the contrary, the TAH system replaces both ventricles, all valves, and has only one controller, negating any common problems routinely seen in BIVAD patients (5). In fact, patients with the TAH system have a higher survival to transplant rate (6,7) and lower incidence of neurological events (8) than patients with BIVAD support.

Since the implantation of the Liotta TAH by Dr. Cooley in 1969 followed by Jarvik-7 (a predecessor of SynCardia 70 cc TAH) by Dr. DeVries in 1982 (9), the Food and Drug Administration (FDA) has approved the 70 cc TAH (Syncardia Systems Inc.,

doi: 10.1111/aor.12854

Received March 2016; revised July 2016; accepted August 2016.

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Tucson, AZ, USA) in 2004 as bridge-to-transplant, and again in 2014 for destination therapy. It is currently the only FDA-approved and CE-marked TAH with more than 1300 patients worldwide and commands a 79% bridge-to-transplant rate (6,7,10). There are a number of inclusion and exclusion criteria that have been established for adults being considered for a 70 cc TAH, as well as for adult and pediatric patients being considered for a 50 cc TAH that must be met in order for the patient to receive a TAH. These criteria were formed to minimize detriment to the patient and to determine if the patient would be able to tolerate TAH placement.

Inclusion criteria to receive a SynCardia Total Artificial Heart are: life-threatening, irreversible biventricular heart failure, patients that are ineligible for cardiac transplantation (e.g., contraindication to immunosuppression, cancer, elevated reactive antibodies), aged between 19 and 75 years, a distance on computerized tomographic (CT) scan of $\geq$10 cm from the anterior vertebral body to sternum inner table at the 10th thoracic vertebra (11), a body surface area (BSA) $\geq$1.7 m^2 for the 70 cc TAH, a BSA $\geq$1.2–1.85 m^2 for the 50 cc TAH, or adequate room in the chest as determined by three-dimensional (3D) imaging assessment or other standard clinical assessments. Some factors for exclusion include: patients on ECMO support greater than 3 days, patients who have experienced a stroke within 30 days prior to proposed implant, and patients with a comorbidity that have a poor prognosis of survival beyond 6 months.

Prior to the 50 cc TAH, implantation of 70 cc TAHs was limited to patients with a larger chest cavity, or who had adequate intrathoracic space to accommodate this device. Preoperative TAH sizing was less of an issue previously when there was only one sizing option available with the 70 cc TAH since the patients with smaller chest cavities simply did not have another option. With the introduction of the 50 cc TAH and its use as an investigational device exemption study, adolescents and smaller adults with irreversible biventricular failure will have a second chance at life. SynCardia Systems Inc. has postulated that a 50 cc TAH would fit smaller statured patients at BSA 1.2–1.7 m^2 or a distance of 7 cm or greater between the anterior vertebral and the 10th thoracic vertebra. Another factor that must be considered is the issue of perfusion and cardiac output. The 50 cc TAH provides a cardiac output of about 3.5–7.5 L/min, while the 70 cc TAH provides a cardiac output of about 4.5–10.5 L/min. In addition to chest cavity sizing and BSA, the TAH device must allow for adequate cardiac output and not limit total body perfusion. Thus, a 70 cc TAH would not always be the best option for smaller patients, both pediatric and adult, as an optimal cardiac output could not be established using a larger device. These are all important parameters that are analyzed clinically and carefully considered prior to selection of TAH sizing. The final step is then to carefully examine whether the selected device can be accommodated into the chest cavity via 3D surgical modeling, reconstruction, and virtual fit.

However, these selection metrics for virtual fit have never been fully characterized. Examining the fit of both 50 and 70 cc TAHs using 3D reconstructions of preoperative CT images for preoperative "virtual implantation" would help surgeons select the proper TAH, eliminating any chance of placing a TAH into a space that cannot accommodate it, resulting in inability to close the chest. In fact, Moore et al. (2015) have found that two patients outside of the proposed sizing criteria would fit a 50 cc TAH (12). However, the in silico study lacked clinical implantation of the 50 cc TAH as validation. Furthermore, there is a limitation with CT images, specifically its static nature that does not take into account the pliability of the surrounding tissues (i.e., the mobility of the diaphragm), which allows for surgical maneuvers that can improve fit (Fig. 1). Herein, we report a series of three cases involving the use of 3D-CT virtual implantation to fit the first North American implantation of a 50 cc TAH. Subsequently, 50 and 70 cc TAHs were placed into two additional patients.

CASE HISTORY

Case 1—the first 50 cc TAH implanted in North America

The patient was a 53-year-old female (BSA 2.1 m^2) status postorthotopic heart transplant 25 years ago with chronic rejection, severe allograft vasculopathy, left ventricular dysfunction, acute on chronic heart failure with moderately depressed left ventricular systolic function on chronic milrinone support. She presented to the emergency department (ED) with severe abdominal pain, nausea, vomiting, and diarrhea with bright red blood per rectum for 2 days. She had multiple comorbidities including persistent sinus tachycardia, pulmonary embolism, non-ST segment myocardial infarction, chronic kidney disease, and chronic pancreatitis. She denied chest pain or shortness of breath. In the ED, she was found to be in metabolic acidosis with

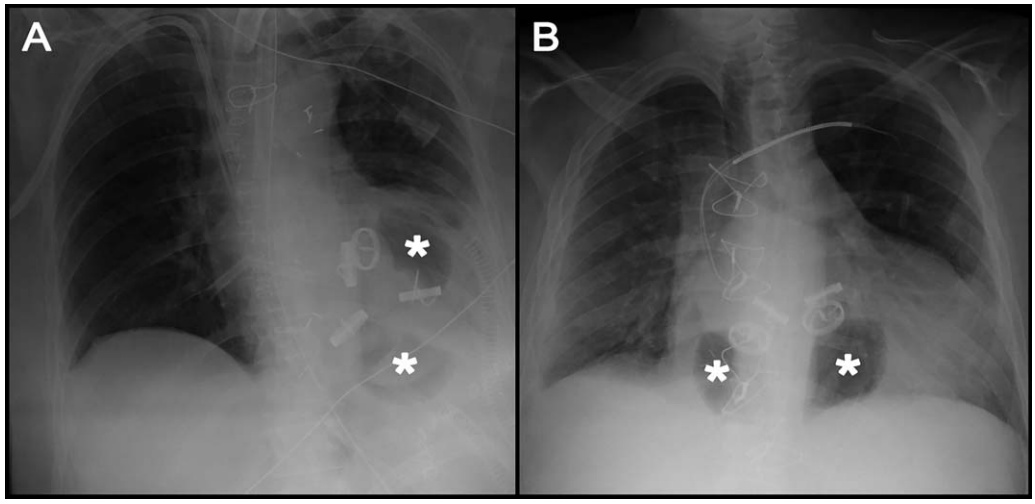

FIG. 1. Atypical TAH positioning. There is atypical positioning of the TAH components (*) on a frontal chest X-ray (A), with the right component being placed below the left component. In contrast, an X-ray from a different, larger patient (B) shows the more conventional side-by-side relationship between the components of the TAH (*).

elevated serum lactate and subsequently became hypotensive to a systolic blood pressure of 80 mm Hg. Her milrinone infusion was discontinued and replaced with dopamine and dobutamine. The patient was then transferred to the cardiac intensive care unit (ICU), and her workup revealed elevated cardiac enzymes and corresponding electrocardiogram (ECG) changes. While in the ICU, the patient underwent pulseless electrical activity (PEA) for which she was resuscitated and intubated. She experienced a second PEA while in the cardiac catheterization lab. An intra-aortic balloon pump was placed in the left femoral artery and despite additional vasoactive medications she continued to show diminished pressures. She had high filling pressures, low cardiac output, and a diffusely hypocontractile heart. She was taken emergently for bilateral extracorporeal biventricular assist device (BIVAD) implantation of Jostra RotaFlow blood pump with Thoratec CentriMag cannulas as bridge to decision. She was in cardiac tamponade overnight and required multiple mediastinal explorations. One week later, we decannulated the BIVAD and implanted a 70 cc TAH after partial restoration of multiple organ failure. However, when closure of the sternum upon implantation of the 70 cc TAH was attempted it resulted in kinking of the patient's abnormally enlarged vena cavae, thus restricting fill volume and blood flow. Consequently, Mersilene tape was used around the lower left rib cage to draw the TAH leftward, but this still compromised flow when closing, so the sternum was left open. The sternal edges were coated with thrombin Gelfoam using Tisseel glue, and then a thick Gore-Tex patch was placed over the open sternum with an Ioban over the patch. The patient was taken back to the operating room later the same day to treat post-operative bleeding. Following placement of the 70 cc TAH, the patient received mediastinal washouts on post-operative day (POD) 4, 7, and 10. On POD 10, the patient also received wound VAC placement with vancomycin. At that point, the chest remained not fully closed, and 3D virtual modeling was used to determine if a 50 cc TAH would allow for chest closure. We then exercised the "one time emergency clause of compassionate use" to replace the 70 cc TAH with a 50 cc TAH with partial removal of a left rib to successfully close the chest on POD 40. Unfortunately, she suffered from gastric perforation, prompting family to withdraw care despite stable cardiopulmonary support on POD 81.

Case 2

The patient was a 22-year-old male with NYHA (New York Heart Association) stage IV systolic heart failure due to a hereditary titin mutation non-ischemic cardiomyopathy with an ejection fraction of 15%. He underwent CentriMag (Thoratec Corp., Pleasanton, CA, USA) BIVAD support using PROTEK Duo cannulas (CardiacAssist Inc., Pittsburgh, PA, USA). He was extubated and ambulated on POD 2 and inotropes weaned. On POD 10, the CentriMag BIVAD was switched to HVAD (HeartWare Inc., Framingham, MA, USA) and CentriMag as bridge to transplant. On POD 34, devices were explanted for the placement of a 50 cc TAH. Preoperative virtual implantation of the 70 cc TAH revealed a tight fit (despite the fact

that the patient did not have a small chest cavity, BSA 1.9 m^2) whereas the 50 cc TAH appeared to fit perfectly. In the operating room the 50 cc TAH went in and the chest was closed without trouble. He is currently awaiting heart transplant.

Case 3

The patient was a 22-year-old female with a history of Marfan's syndrome, non-ischemic cardiomyopathy, ascending arch replacement, aortic valve replacement, and type B aortic dissection who presented with decompensated heart failure. Her automatic implantable cardioverter defibrillator (AICD) was explanted and a redo sternotomy was performed followed by placement of a 70 cc TAH. Interestingly, this patient (BSA 1.5 m^2) had a relatively small chest cavity with a pectus excavatum; however, she had a large heart and virtual implantation of the 70 cc TAH demonstrated a good fit. In the operating room the 70 cc TAH went in and the chest was closed without trouble. She is currently awaiting heart transplant.

MATERIALS AND METHODS

There are several software programs on the market that allow the user to superimpose CT data sets. Our methodology is to load CT scans of potential TAH patients into Amide's Medical Image Data Examiner (AMIDE), along with CT scans of both 50 and 70 cc SynCardia TAHs. AMIDE is an open-source software tool for displaying and analyzing multimodality volumetric medical images that runs on multiple operating systems. Of note, each disarticulated component of the 50 and 70 cc TAHs (right and left) was scanned separately on a FLASH CT Scanner (Siemens AG Healthcare, Forchheim Germany) utilizing a soft tissue reconstruction kernal and thin (0.6 mm) slice reconstruction with a fixed kVp of 120 and mAs of 120. The SynCardia TAH has two halves that are not fused, but rather Velcro together, which allows for greater flexibility. The two halves of the TAH can be fully disarticulated and placed above, below, or beside each other as needed (Fig. 1) during virtual fitting and actual patient implantation.

The TAH CT scans were loaded into the AMIDE post-processing software, where they could be superimposed on the CT data sets from a patient's chest CT. The patient CT scans were helically acquired and reconstructed by utilizing a smooth (soft tissue) kernel, and thin slice reconstruction thickness ($\leq$3 mm) was also loaded into the AMIDE post-processing software.

In order to determine difficulty of fit, the following process was used: The left ventricular (LV) component was virtually placed first with the LV inflow valve positioned between 1 and 3 cm distal to the mitral annulus. There needs to be an adequate cuff of residual ventricular tissue left behind after excision so that the LV component can be securely sutured in place. There is flexibility regarding the size of this ventricular cuff and also flexibility in how much of the corresponding sewing ring on the TAH can be incorporated so that when the TAH is sutured into place the inflow valve of the component can be just below the mitral annulus or there could be a few centimeters of space distal to the annulus.

The LV component was then rotated so the outflow valve component was placed as close as possible to the patient's aortic annulus and the "apical" aspect of the component was directed toward the patient's cardiac apex. The right ventricular (RV) component was virtually implanted using the same techniques as described for the LV components. Once both components were superimposed on the data sets they were rotated and translated in 3D space (using axial, sagittal, and coronal imaging reconstructions) relative to each other to determine the best possible fit with the following constraints. The inflow valves had to stay centered and within 1–3 cm of their respective AV valve annulus. The RV and LV components could not overlap at all: the RV component could not overlap the anterior chest wall, and the LV component could not extend beyond the lateral wall of the LV (into the adjacent lung/ingula). The RV and LV components can disarticulate, allowing for great anatomical flexibility when placing, but one thing that became clear was the fact that even with this manipulation, the TAHs rarely fit entirely within the space currently occupied by the patient's heart.

There was a fear that placing too large of a TAH into too small of a space would lead to venous kinking and occlusion or difficulty with chest wall closure. In order to provide some controls to determine what amount of overlap between the device and the anterior chest wall (or lateral wall of the LV) was acceptable, this process was performed retrospectively on two patients that had already had 70 cc TAHs successfully placed. Virtual implantation of 70 cc TAHs into these patients demonstrated that 1–2 cm of overlap between the anterior chest wall or left lung was acceptable, confirmed by successful implantation of the 70 cc TAHs by a surgeon. We postulate that this "wiggle room" is anatomically acceptable due to the

TABLE 1. *SynCardia Total Artificial Heart virtual fitting, standard fit criteria, and patient implantation*

Pt	Age (yrs)	BSA (m^2)	LV diameter on CT scan (cm)	T10-sternum distance (cm)	Meets standard fit criteria for 70 cc TAH	3D virtual implant successful	TAH-t device size successfully placed
1	53	2.1	6.5	12.5	Yes	Yes	50 cc
2	22	1.9	7.3	9.6	No	Yes	50 cc
3	22	1.5	5.3	11.4	No	Yes	70 cc

3D, 3-dimensional; BSA, body surface area; TAH-t, Total Artificial Heart, SynCardia Systems, Tucson, AZ.

plasticity of the anatomy. The CT shows fixed anatomy taken at one point in time and makes no allowance for the surgeon's ability to manipulate anatomy in order to improve the "fit" of the TAH. If there was more than 2 cm of overlap with the 70 cc TAH, it was deemed as "too large" and the 50 cc was virtually implanted.

In brief, once the patient's CT scan is loaded into the system we first insert the left component into the space occupied by the left ventricle. The mitral annulus is relatively fixed in position within the chest and serves as the anchor point for our virtual TAH implantation. The location of the pumping chamber itself and of the aortic graft is less important as there is flexibility in positioning of these devices. The left component is placed as posteriorly as possible to allow maximum space anteriorly for the right component. The right component is then virtually implanted using the tricuspid annulus as the anchor point. Sometimes the components may need to be translated or rotated relative to one another to ensure best possible fit. As long as the mitral and tricuspid valves are at or near (1–2 cm distal) their respective annulus the location of the chamber and outflow grafts can be manipulated to ensure best possible fit. After the TAH is manipulated into place, we examine the relationship between the right component and the anterior chest wall to predict if there will be any difficulty with chest closure.

RESULTS

Ultimately, if the TAH can fit in the space remaining once the ventricles are resected, then there should be no issues with chest closure. If the TAH is larger than the space left behind after the ventricles are removed, then there is a chance that the chest will not close or that closure will result in compression of the inferior vena cava (IVC) or pulmonary veins. While the size of the chest cavity is important, the size of the heart is of equal or greater importance. If the patient has a very large heart, left ventricle end diastolic diameter (LVEDD) greater than 6 cm, it is usually straightforward to place a TAH regardless of the size of the thoracic cavity. The volume left after resection of the ventricles is large enough to accommodate the TAH. Patients with average-sized hearts, as well as average-sized thoracic cavities, pose the greatest challenge.

Herein, we have used preoperative 3D CT imaging to perform prospective "virtual implantation" of 50 and 70 cc TAHs in patients as described (Table 1). The first patient in this case series had a BSA of 2.1 m^2 and T10 distance of 11.4 cm. Both measurements indicated that a 70 cc TAH should fit and allow for post-op chest closure. Unfortunately, the latter was not the case as she had a relatively average-sized heart with LVEDD of approximately 5 cm and an abnormally enlarged inferior vena cava. Two weeks following placement of the 70 cc TAH, to allow for closure of the sternum and waiting for swelling to subside, we explanted the intracorporeal 70 cc TAH, put the patient on central cardiopulmonary bypass, and implanted a new 50 cc TAH, which resulted in successful chest closure (Fig. 1). This is the first reported case of a successful implantation of a smaller-sized 50 cc TAH in a patient that was achieved with 3D virtual implantation (Fig. 2A, B). Retrospective "virtual implantation" of the 70 cc TAH in this patient demonstrated that the 70 cc TAH was not going to fit. Had the virtual implantation been done prospectively instead of retrospectively for this first case, a 50 cc TAH might have been placed initially saving the patient unnecessary operations.

Following the first successful 50 cc TAH implantation, similar 3D virtual modeling was used for two successive patients. We were able to assess TAH fit preoperatively which thus resulted in a successful execution of TAH implantation and chest closure. In Patient 2, virtual implantation modeling showed that a 70 cc TAH would have a tight fit despite a BSA of 1.9 m^2, whereas a 50 cc TAH would fit quite easily. After FDA approval for IDE study, HVAD and the CentriMag devices were removed and replaced with a 50 cc TAH for bridge-to-transplant based on RVAD wean failure

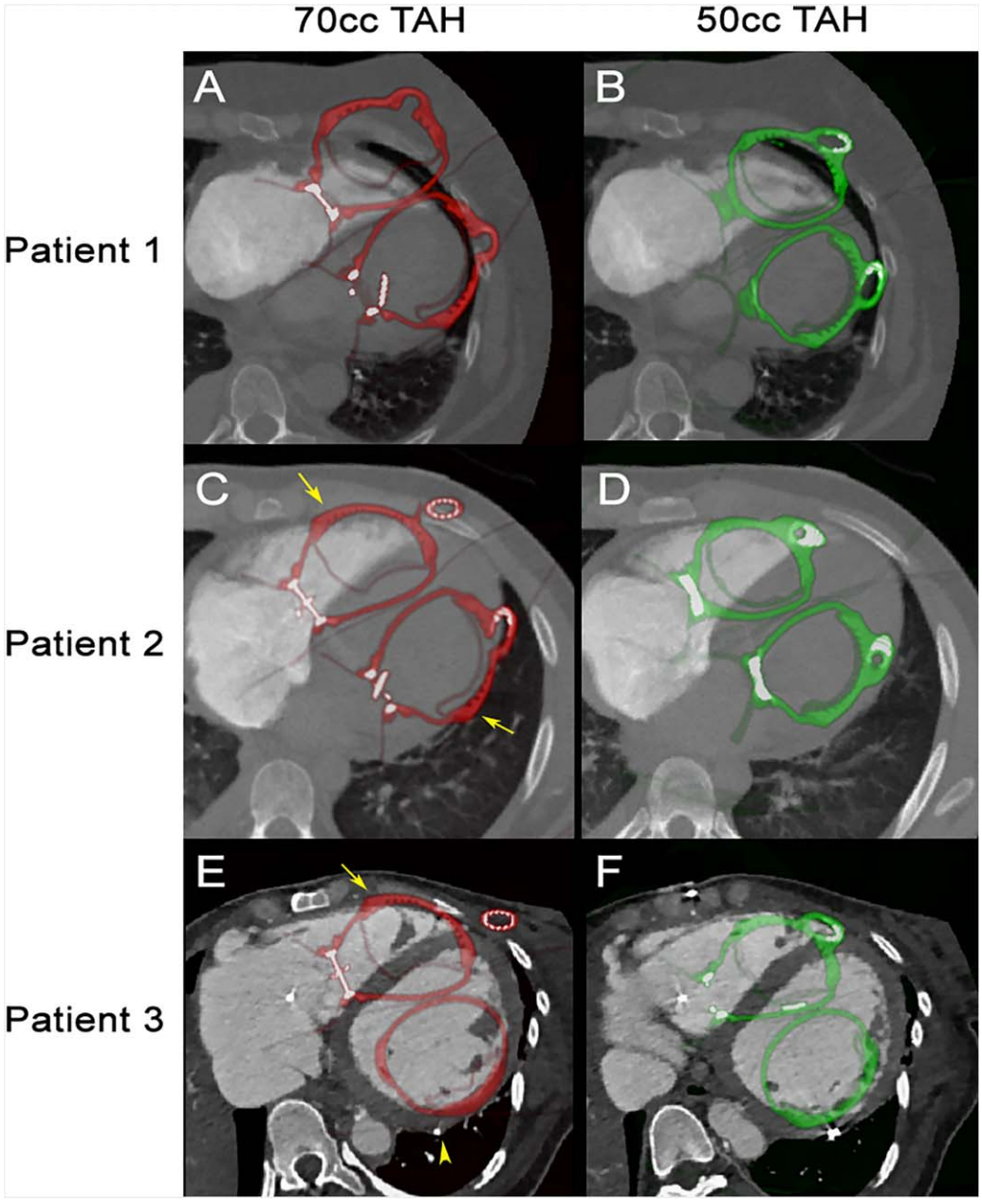

FIG. 2. (A, B) Virtual implantation of a 70 and 50 cc TAH into Patient 1. The 70 cc TAH (A) depicted in red shows an impossible fit, whereas the superimposed 50 cc TAH (B) shown in green demonstrates potential fit into Patient 1. Neither device fits perfectly due to the patient's left ventricle being only mildly enlarged and normal size of the right ventricle; however, successful implantation of the 50 cc device was possible after surgical manipulation of the surrounding organs and diaphragm. (C, D) Virtual implantation of a 70 and 50 cc TAH into Patient 2. Part of the 70 cc TAH (C) projects over the anterior chest wall and beyond the lateral wall of the LV posteriorly (arrows), indicating extensive surgical maneuvering is required for successful implantation. The 50 cc device (D) projects entirely within the ventricular cavities. From the virtual modeling, the decision was made to place the 50 cc TAH, which was successfully implanted into the patient without complication. (E, F) Virtual implantation of a 70 and 50 cc TAH into Patient 3. The patient has pectus excavatum with anteroposterior chest cavity diameter of 9.6 cm at T10 level, indicating a low probability of successful implantation of a 70 cc TAH. On virtual implantation of the 70 cc device (E), the RV component impinges upon the anterior chest wall (arrow) but the LV is dilated, providing extra space posteriorly (arrow head) that allows the surgeon to maneuver for an appropriate fitting. This predicts a high likelihood of successful implantation, despite the small thoracic cavity. Virtual implantation of a 50 cc TAH shows adequate space for successful implantation (F). The decision was made to place the 70 cc device, which was successfully implanted without complication; this highlights the limitation of static CT images, which do not take into consideration the dynamics of the diaphragm, pliability of surrounding tissues, and effect of surgical maneuvers. We recommend factoring in approximately 1 cm of extra space when performing virtual TAH implantation to account for such factors. [Color figure can be viewed at wileyonlinelibrary.com]

in spite of extensive fluid removal during the BIVAD support (Fig. 2C, D). In Patient 3, virtual implantation showed the 70 cc TAH would fit despite her relatively small thoracic cavity (BSA 1.5 m^2). She had a larger-sized heart with an LVEDD of greater than 7 cm. Hence, an automatic implantable cardioverter defibrillator was explanted and a 70 cc TAH was implanted with successful chest closure (Fig. 2E, F).

To the best of our knowledge, this is the first time a 50 cc TAH was successfully implanted in North America (13). This is also the first full report of utilization of 3D reconstructed images and virtual modeling for the implantation of 50 and 70 cc TAHs using 3D chest CT preoperatively. As reported, all three patients received clinical implants of the properly sized TAH without complications.

DISCUSSION

The 3D reconstruction of CT images is a technique that is widely used to assess volume of devices and organs. As part of the preoperative planning, some centers create a 3D model of the device to be implanted that is virtually placed into reconstructed CT images of the patient's chest in order to assess if the device will fit within the patient's thoracic cage. This assessment is made based on CT images acquired of the thoracic cavity. These images are acquired while the patient is holding their breath at maximum inspiratory effort to minimize artifact to motion. The act of breathing is dynamic and involves several muscles. CT images are acquired at a single time point during the respiratory cycle, limiting our ability to assess the physiologic changes that happen within the thoracic cavity with normal respiration.

In considering methods that would further improve 3D virtual fitting, we hypothesize that the use of magnetic resonance imaging (MRI) would give additional information. MRI is a relatively new and rapidly evolving imaging modality that can allow improved evaluation of the thoracic cavity during respiration to better assess these physiologic changes that CT scans cannot detect. Thus, real-time dynamic MRI of the chest could be performed during inspiratory and expiratory using a single-shot steady-state free-precession balanced gradient echo sequence (Tru-FISP). The goal of this imaging would be to gain a dynamic understanding of the anatomy surrounding the patient's heart to better assist with TAH placement. Knowledge obtained from this imaging would help the surgeons determine approximately how much anatomic flexibility was available to assist with TAH placement. Factors such as diaphragmatic excursion and anterior chest wall expansion would be taken into account.

We believe that preoperative planning based on dynamic chest MRI acquisition can better depict volumetric changes in the thoracic cage and detect physiologic adjustments of the respiratory muscles. Moreover, assessments based on static CT images also do not take into consideration small surgical procedures that can be done to expand the volumetric capacity of the thoracic cavity, such as diaphragmatic plication, which was used in the first patient case to allow the 50 cc TAH to fit into the cavity and allow for closure (Fig. 2A, B).

Although MRI has a lot of potential for preoperative device sizing, preoperative virtual implantation of a device into a chest CT is a relatively quick and easy way to assess device fit prior to surgery. A CT scan is comparatively cheaper, faster, and more widely available. Many patients undergoing evaluation for TAH placement are too sick to get an MRI or may have contraindications to MRI such as being pacer-dependent. In these patients, checking device fit preoperatively with CT is feasible. Metrics such as body surface area (BSA) > 1.7 m^2, LVEDD > 6 cm, and intrathoracic antero-posterior dimension at the level of the T10 vertebral body (T10) of > 10 cm have been used as cut-offs to determine whether the patient's thoracic cavity can accommodate a 70 cc TAH (14).

Preoperative "virtual implantation" of TAHs into a patient's chest CT appears to be a helpful method for determining preoperative "fit" of TAH. This is especially important now since the 50 cc TAH has been added to the armamentarium, and there are currently no guidelines for minimum thoracic cavity size for the 50 cc TAH. As stressed before, the limitation of this methodology is the reliance on static CT imaging. Previous techniques to improve fitting of the TAH within the chest involves a 3D reconstruction of the chest CT coupled with a 3D rendering of the 50 and 70 cc TAH (12). However, these fitting techniques were part of a study that was a retrospective analysis of the 70 cc TAH for the virtual implantation of a 50 cc TAH.

Moreover, it is important to recognize that the implantation of various sizes of TAHs is consistent with the rules of personalized medicine, whereby surgeons have the option of selecting the medical device most suitable for optimized treatment of a patient. In this case, multiple parameters (standard fit, LV diameter, chest cavity elasticity, etc.) have been investigated by radiologists via CT to further

inform the surgeons of the available "wiggle room" in each respective patient. The plasticity of an individual's anatomy based on physiological and pathogenic conditions determines whether or not a patient can actually accommodate a TAH with a tight fit upon 3D virtual fitting. Multiple selection criteria must be considered for each individual patient since there are no exact rules that apply to all patients when it comes to choosing the optimal TAH size for implantation.

CONCLUSION

Our article documents the first time a 50 cc TAH was implanted successfully in North America after preoperative virtual fitting. The thoracic cavity is dynamic and changes in size and configuration with respiration. Patient 3 (Fig. 2E, F) is an example of how surgical maneuvers could be used to create more space in the chest such that a device that showed a tight virtual fit could still be implanted successfully. MRI has potential for improved preoperative sizing since it is a more dynamic imaging technique. Therefore, a combination of multiple imagining modalities, including CT and MRI, can be used to aid a cardiothoracic surgeon in predicting through "virtual implantation" whether or not there will be difficulty with full chest closure following TAH placement.

Acknowledgments: The authors would like to acknowledge the patients and their families.

Consent: Written informed consent was obtained from the patient for publication of this case report and any accompanying images. A copy of the written consent is available for review by the Editor-in-Chief.

Conflict of Interest: None declared.

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