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MAIN TEXT

Comparing left ventricular assist device inflow cannula angle between median sternotomy and thoracotomy using 3D reconstructions

Madeleine Pearman[1,2] | **Sam Emmanuel**[1,2,3,4] | **Paul Jansz**[1,2,3,4] | **Alasdair Watson**[1] | **Mark Connellan**[1] | **Arjun Iyer**[1] | **Sumita Barua**[1,3,4] | **Christopher Simon Hayward**[1,3,4]

[1]St Vincent's Hospital, Sydney, Darlinghurst, New South Wales, Australia

[2]School of Medicine, University of Notre Dame, Sydney, Chippendale, New South Wales, Australia

[3]School of Medicine, University of New South Wales, Sydney, Kensington, New South Wales, Australia

[4]Victor Chang Cardiac Research Institute, Sydney, New South Wales, Australia

Correspondence
Christopher Simon Hayward, Cardiology Department, St Vincent's Hospital, 390 Victoria Street, Darlinghurst, NSW 2010, Australia.
Email: cshayward@stvincents.com.au

Abstract

Background: Left ventricular assist device (LVAD) implantation via thoracotomy has many potential advantages compared to conventional sternotomy, including improved inflow cannula (IFC) positioning. We compared the difference in IFC angles, postoperative, and long-term outcomes for patients with LVADs implanted via thoracotomy and sternotomy.

Methods: A single-center, retrospective analysis of 14 patients who underwent thoracotomy implantation was performed and matched with 28 patients who underwent sternotomy LVAD implantations for a total of 42 patients. Inclusion required a minimum LVAD support duration of 30 days and excluded concomitant procedures. A postoperative CT-chest was used to measure the angle the between the IFC and mitral valve in two-dimensions and results were compared with three-dimensional reconstruction using the same CT chest. Outcome data were extracted from medical records.

Results: There was no significant difference in gender, INTERMACS score, BMI, or age between the two groups. Median cardiopulmonary bypass time was longer in the thoracotomy group compared to the sternotomy group, 107 min (86–122) versus 76 min (56–93), $p < 0.01$. 3D reconstructions revealed less deviation of the IFC away from the mitral valve in devices implanted via thoracotomy compared to sternotomy, median (IQR) angle 16.3° (13.9°–21.0°) versus 23.2° (17.9°–26.4°), $p < 0.01$. Rates of pump thrombosis, stroke, and gastrointestinal bleeding were not significantly different.

Conclusions: Devices implanted via thoracotomy demonstrated less deviation away from mitral valve. However, there was no difference in morbidity between the two approaches. 3D reconstruction of the heart is an innovative technique to measure angulation and is clinically advantageous when compared to 2D imaging.

KEYWORDS
device angulation continuous flow pumps, device positioning, thrombosis, ventricular assist devices

1 | INTRODUCTION

Globally, heart failure remains a significant cause of morbidity and mortality, affecting 1%–2% of the adult population.[1] With this number expected to rise in the context of an aging population, the 5% of patients who will progress to end-stage heart failure refractory to medical therapy[2] present an increasing burden on healthcare services. Although heart transplantation remains the gold standard for these patients, shortage of donors limits accessibility. Durable mechanical circulatory support aims to fill this gap as devices can be used as a bridge to transplant, bridge to candidacy, bridge to recovery, or destination therapy, the latter of which represent approximately 75% of global left ventricular assist device (LVAD) implants.[3]

Despite survival rates of 82.3% at 1 year,[4] LVADs are associated with significant adverse hemodynamic events including stroke, gastrointestinal bleeding, and pump thrombosis, with 60% of patients experiencing an LVAD-related complication within the first 6 months.[5] This is in part attributed to the need for anticoagulation and endothelial changes associated with continuous flow.[6] These issues may be compounded by suboptimal device position.

The landmark LATERAL trial confirmed the safety and efficacy of LVAD implantation via thoracotomy[7] and 2-year follow up demonstrated reduced overall non-surgical bleeding events in those who were implanted via thoracotomy compared to conventional sternotomy, as well as 95% freedom from disabling stroke.[8] Implantation via thoracotomy may mitigate some of the technical challenges of implantation as it allows for improved visualization and flexibility,[9] allowing more optimal inflow cannula placement. We assessed the impact of surgical approach on optimal cannula placement by comparing outcomes between lateral thoracotomy and conventional sternotomy approaches for LVAD implantation.

2 | METHODS

Forty-two patients who underwent implantation of the Medtronic Ventricular Assist Device (HVAD) (Medtronic, Minneapolis, MN) at St Vincent's Hospital (Sydney, Australia) were studied. All 14 patients who had the device implanted via thoracotomy at our center were included. This approach involves a left anterolateral incision in the fifth intercostal space for the LVAD pump and a right anterior thoracotomy in second intercostal space to implant the outflow graft. These were matched with 28 consecutive patients who had the device implanted via median sternotomy in the same time period from September 2015 to February 2020. Surgical technique was chosen by the surgeon based on familiarity with operative technique and patient factors, such as frailty and likelihood of compliance with sternal precautions.

A criterion for inclusion in this study was a minimum LVAD support duration of 30 days. Patients who underwent LVAD implantation with concomitant procedures such as aortic valve replacements, atrial septal defect closure, tricuspid valve repair, or biventricular VAD implants were excluded. Adverse outcome data were extracted from online medical records and mechanical circulatory support database. Institutional ethical approval was obtained (St Vincent's and Mater Health Human Research Ethics Committee: 2020/PID01371).

For both the 2D and 3D scans, two independent reviewers measured the angles individually to demonstrate concordance and to check accuracy of the measurement techniques. For all patients, we aimed to use the first available CT. The average time between LVAD implantation and the CT used for device measurement was 49 days.

2.1 | 3D angle measurements

Open-source single-software solution 3D Slicer (Harvard University/National Institute of Health, http://www.slicer.org) was used to create a 3D reconstruction of the ventricular assist device (VAD) within the left heart from the CT scan imported into the software. We aimed to use the first postoperative CT scan; however, non-contrast scans could not be accurately reconstructed. Therefore, for four patients, we used a subsequent, contrast-enhanced scan. The left atrium, left ventricle, aorta, outflow graft, and LVAD were reconstructed as 3D images. To calculate inflow cannula angulation, the first arm of the angle was drawn from the mid-point of the mitral annulus (centroid) to the center of the base of the LVAD, representing the "ideal" angle. The second arm was drawn from the middle of the base of the LVAD through the middle of the inflow cannula, offering the "actual" direction of flow, thus giving us the angle of deviation, see Figure 1. The optimal angle would be 0 degrees when using this method, meaning the inflow cannula is directly pointing toward the mitral valve centroid.

2.2 | 2D angle measurements—Axial and coronal CT scan

The first postoperative contrast CT scan of the chest was used to measure the angle between the inflow cannula and mitral valve in both axial and coronal planes. Due to the orientation of the heart, the mitral valve and LVAD are not seen in the same slice in the CT scan. Once the mitral valve was visualized, the midpoint was marked, and that marking was carried across all slices of the scan, depicted as a red X in Figures 2 and 3. This allowed us to measure the angle between the position of the LVAD inflow cannula and the position of the mitral valve. The first arm of the angle was drawn from the mitral valve marking to the base of the LVAD. This arm demonstrated the "ideal" direction of flow, depicted in blue in Figures 2 and 3. The second arm was drawn from the base of the LVAD through the middle of the inflow cannula, representing the "actual" direction of flow depicted in green in Figures 2 and 3. The difference between these directions was measured, providing the degree of angulation.

2.3 | 2D angle measurements—Scout shot

We also assessed the usefulness of the scout shot image of the CT scan to measure inflow cannula angulation. Given

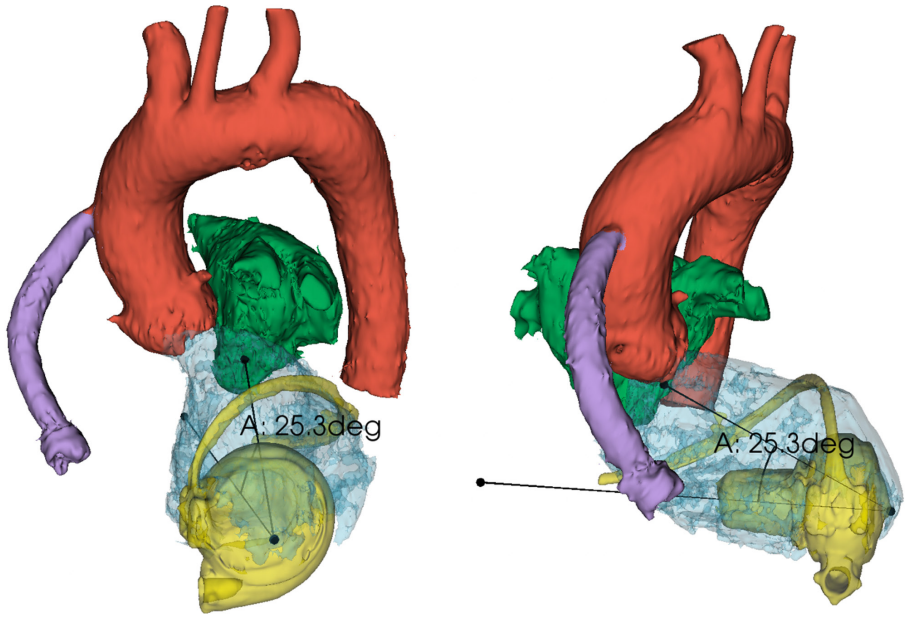

FIGURE 1 Angle measurement in 3D reconstruction [Color figure can be viewed at wileyonlinelibrary.com]

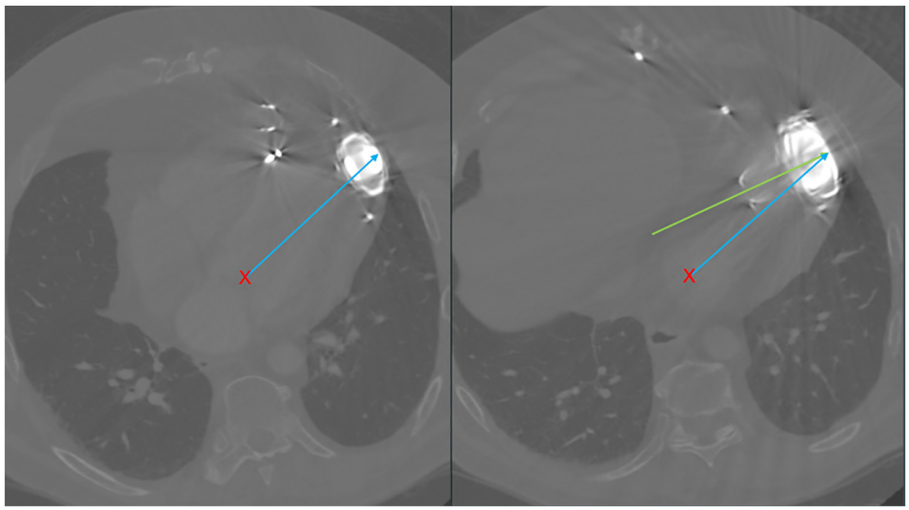

FIGURE 2 Angle measurement in axial plane [Color figure can be viewed at wileyonlinelibrary.com]

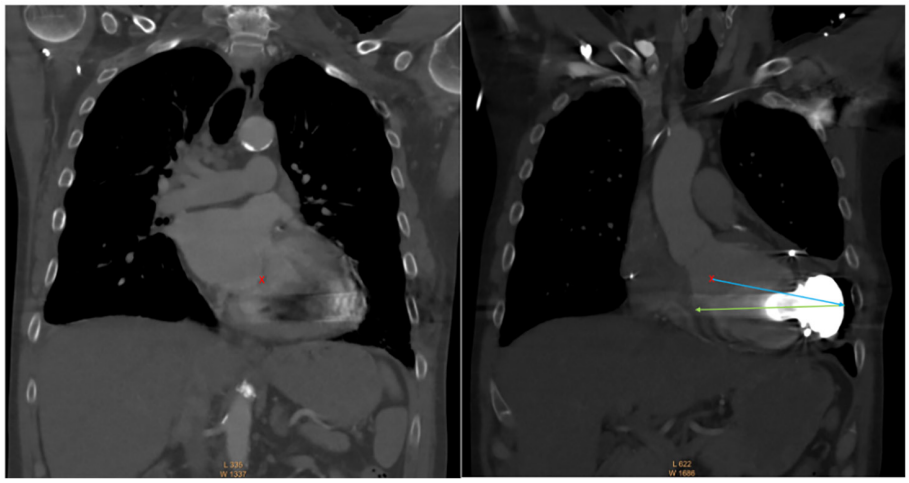

FIGURE 3 Angle measurement in coronal plane [Color figure can be viewed at wileyonlinelibrary.com]

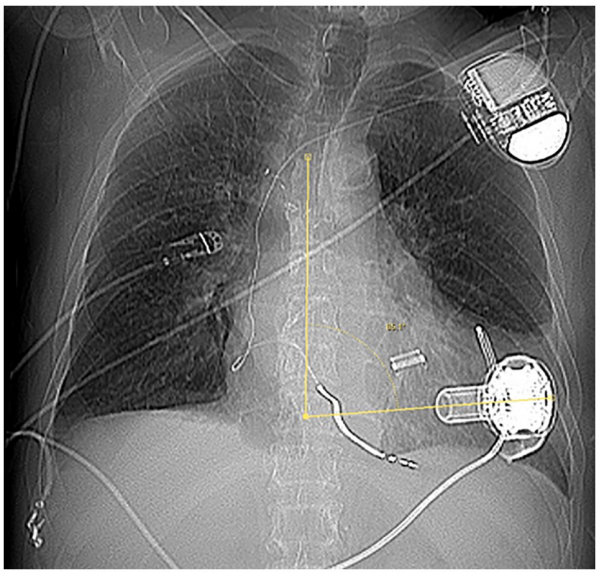

FIGURE 4 Angle measurement in Scout shot [Color figure can be viewed at wileyonlinelibrary.com]

that this is a single supine 2D image, we felt it would be representative of a chest x-ray, and therefore may offer utility in the immediate postoperative setting. The Y axis was formed from a vertical line drawn down the vertebral column and the X axis was drawn perpendicular to this, intersecting with the middle of the LVAD, through the inflow cannula (Figure 4).

2.4 | Statistical analysis

Statistical analysis was carried out using IBM SPSS v27 (Armonk, NY: IBM Corp). Descriptive statistics are displayed as number (percentage) for categorical data, whereas continuous data are presented as median (interquartile range). Categorical data were compared using the chi-squared test, whereas continuous data were compared using the Mann–Whitney *U* test. Interclass correlation coefficient analysis was carried out to ensure inter-rate reliability.

3 | RESULTS

3.1 | Demographic and preoperative data

There was no significant difference between the two cohorts in terms of age, sex, or BMI. Dilated cardiomyopathy was most common etiology, followed by ischemic cardiomyopathy ($p = 1.0$). In terms of severity of heart failure, there was no significant difference between the two groups with the majority being classed as INTERMACS II ($p = 0.65$; Table 1).

3.2 | Intraoperative outcomes

Cardiopulmonary bypass time was shorter in the sternotomy group with a median time of 76 min (56–93) compared with 107 min (86–122) in the thoracotomy group ($p < 0.01$). Operation duration was longer in the thoracotomy group, with a median time of 5 h and 8 min (4:16–6:36) compared to the sternotomy group with 4 h and 25 min (3:30–5:09), $p = 0.05$. There was no difference in administration of blood products intraoperatively (Table 2).

3.3 | Postoperative outcomes

While the postoperative course for patients of both groups was similar, those who underwent sternotomy implantation had a higher packed red blood cell requirement

TABLE 1 Demographic and preoperative data

	Sternotomy ($n = 28$)	Thoracotomy ($n = 14$)	Significance
Age at LVAD implantation	58.7 (49.5–63.8)	56.9 (51.6–62.7)	$p = 0.67$
Sex	Male: 23 (82%)	Male: 9 (64%)	$p = 0.26$
BMI kg/m^2	27.9 (24.3–29.9)	24.9 (22.9–27.3)	$p = 0.11$
BSA m^2	2.0 (1.8–2.1)	1.9 (1.7–2.1)	$p = 0.38$
INTERMACS	I 4 (14%)	I 1 (7%)	$p = 0.65$
	II 13 (46%)	II 7 (50%)	
	III 10 (36%)	III 4 (29%)	
	IV 1 (4%)	IV 2 (14%)	
Heart failure etiology	DCM 18 (64%)	DCM 9 (64%)	$p = 1.0$
	ICM 9 (32%)	ICM 5 (36%)	
	Viral myocarditis 1 (4%)	Viral myocarditis 0 (0%)	
Preoperative eGFR ml/min/BSA	64 (52–78)	57 (48–76)	$p = 0.47$
Preoperative Hemoglobin g/dl	131 (99–139)	130 (117–155)	$p = 0.13$
Left ventricular end diastolic diameter mm	64 (58–68)	67 (59–80)	$p = 0.49$

Note: Continuous data presented as median (25th–75th quartiles), categorical data presented as number (percent).

Abbreviations: BMI, body mass index; BSA, body surface area; INTERMACS, Interagency Registry for Mechanically Assisted Circulatory Support; eGFR, estimated glomerular filtration rate.

TABLE 2 Intraoperative data

	Sternotomy ($n = 28$)	Thoracotomy ($n = 14$)	Significance
Operation length (hours)	4:25 (3:30–5:09)	5:08 (4:16–6:36)	$p = 0.05$
CPB time (mins)	76 (56–93)	107 (86–122)	$p < 0.01$
PRBC (units)	0 (0–1)	0 (0–0)	$p = 0.67$
Cryoprecipitate (units)	0 (0–5)	0 (0–4)	$p = 0.81$
Fresh frozen plasma (units)	0 (0–0)	0 (0–2)	$p = 0.42$
Platelets (units)	0 (0–1)	0 (0–1)	$p = 0.88$
Return to theater	4 (14%)	1 (7%)	$p = 0.79$

Note: Continuous data presented as median (25th–75th quartiles), categorical data presented as number (percent).

Abbreviations: CPB, cardiopulmonary bypass; PRBC, packed red blood cells.

compared to the thoracotomy group. However, this difference lies in the interquartile range and the p value is borderline significant, $p = 0.04$, casting doubt on the clinical significance of this finding.

There was no statistically significant difference in rates of extracorporeal membrane oxygenation (ECMO) support, immediate postoperative hemoglobin, kidney function, or serum lactate dehydrogenase. Ventilation time and overall postoperative length of stay was similar between the two groups (Table 3).

3.4 | Long term outcomes

There was no statistically significant difference between rates of adverse hemodynamic events with the two groups experiencing similar rates of pump thrombosis, gastrointestinal bleeding, and stroke. The length of support time from LVAD implantation to transplant was not significantly different with a median of 360 days (211–471) in the sternotomy group compared to 328 days (243–510) in the thoracotomy group ($p = 1.0$), (Table 4).

3.5 | Inflow cannula angle

Using 3D reconstructions, there was a statistically significant difference between LVADs implanted via sternotomy and thoracotomy, with a median angulation of 23.2 and 16.3, respectively ($p < 0.01$; Table 5). This difference however was not reflected in other modalities to measure device angulation. There was no significant difference between

TABLE 3 Postoperative data

	Sternotomy ($n = 28$)	Thoracotomy ($n = 14$)	Significance
VPA ECMO	5 (18%)	1 (7%)	$p = 0.65$
ECMO	1 (4%)	2 (14%)	$p = 0.25$
PRBC given in ICU (units)	0 (0–1)	0 (0–0)	$p = 0.04$
Cryoprecipitate given in ICU (units)	0 (0–0)	0 (0–0)	$p = 1.0$
Fresh frozen plasma given in ICU (units)	0 (0–0)	0 (0–0)	$p = 1.0$
Platelets given in ICU (units)	0 (0–0)	0 (0–0)	$p = 1.0$
Ventilation time (hours)	25 (18–158)	25 (19–69)	$p = 0.77$
ICU length of stay (days)	8 (4–15)	6 (4–8)	$p = 0.52$
Postop length of stay (days)	32 (21–53)	25 (22–34)	$p = 0.31$
Hemoglobin g/dl	99 (90–114)	104 (94–123)	$p = 0.27$
eGFR ml/min/BSA	74 (52–88)	72 (58–78)	$p = 0.64$
LDH at 1 month U/L	419 (376–518)	452 (390–519)	$p = 0.71$

Note: Continuous data presented as median (25th–75th quartiles), categorical data presented as number (percent).

Abbreviations: ECMO, extracorporeal membrane oxygenation; eGFR, estimated glomerular filtration rate; ICU, intensive care unit; LDH, lactate dehydrogenase; PRBC, packed red blood cells; VPA ECMO, venopulmonary arterial extracorporeal membrane oxygenation; .

TABLE 4 Long term outcome data

	Sternotomy ($n = 28$)	Thoracotomy ($n = 14$)	Significance
Pump thrombosis	7 (25%)	3 (21%)	$p = 1.0$
Gastrointestinal bleeding	5 (18%)	0 (0%)	$p = 0.14$
Stroke (non-TIA)	Ischemic 5 (18%) Hemorrhagic 0 (0%) Mixed/other 1 (4%)	Ischemic 2 (14%) Hemorrhagic 2 (14%) Mixed/other 0 (0%)	$p = 0.71$
Support duration (days)	360 (211–471)	328 (243–510)	$p = 1.0$
Death on pump	4 (14%)	3 (21%)	$p = 0.67$

Note: Continuous data presented as median (25th–75th quartiles), categorical data presented as number (percent).

the two surgical approaches when measured using scout shot images, axial, or coronal CT scans of the chest.

3.6 | Measurement techniques and accuracy

Overall interobserver reliability was excellent between both reviewers (Table S1 in the Data Supplement).

3.6.1 | 3D Reconstruction

3D reconstruction demonstrated excellent interobserver reliability, with an intraclass correlation coefficient of 0.92.

3.6.2 | 2D axial and coronal

The axial view provided excellent interobserver reliability of 0.98, which is compared to an intraclass correlation coefficient of 0.75 on the coronal view. This is likely due to the mitral valve being more easily identifiable on the axial view rather than the coronal view.

3.6.3 | Scout shot

Scout shot CT images were used as a surrogate of immediate postoperative imaging to assess malpositioning of the device. By using the spine as an anchoring point to account for patient rotation, we hoped to improve the

TABLE 5 Inflow cannula angles

	Sternotomy ($n = 28$)	Thoracotomy ($n = 14$)	Significance
3D reconstruction	23.2° (17.9–26.4)	16.3° (13.9–21.0)	$p < 0.01$
Scout shot	95.1° (90.9–119.5)	97.7° (90.8–108.2)	$p = 0.87$
Axial CT	10.3° (5.8–25.2)	9.6° (4.5–14.2)	$p = 0.39$
Coronal CT	14.0° (10.3–21.2)	14.5° (9.6–16.9)	$p = 0.91$

Note: Continuous data presented as median (25th–75th quartiles); categorical data presented as number (percent).

accuracy of our measurements. While the interobserver reliability using the intraclass correlation coefficient showed a good concordance of 0.99, we found that this method did not prove to be a precise method of assessing device angulation. Significant deviation obviously seen on the scan was not reflected in the angles due to the poorly defined intracardiac structures visible on x-ray.

4 | DISCUSSION

LVADs implanted via thoracotomy were more closely aligned to the mitral valve centroid in three-dimensional reconstruction compared to sternotomy. This suggests more optimal placement of the device and expected favorable intraventricular hemodynamics. Within our small cohort, this was not reflected in outcomes as there were similar rates of stroke, gastrointestinal bleeding, and pump thrombosis between the two groups.

4.1 | Importance of inflow cannula angle

LVADs create a thrombogenic environment which can classically be articulated by Virchow's triad.[10] What occurs outside the LVAD regarding endothelial injury, hypercoagulability and stasis can be extrapolated and applied to the environment within the LVAD-supported heart. In a healthy heart, the three-dimensional diastolic vortical flow with cardiac contraction allows for washout of the entire ventricle. As the ventricle fills, blood travels in a large clockwise vortex moving apically.[11] However, the insertion of the inflow cannula proximal to the left ventricular outflow tract creates a zone of stasis. Aberrant flow patterns induced by the LVAD promote thrombus formation by altering fluid dynamics, which feature areas of hemolysis and stasis. While the HVAD has an integrated Lavare pattern of preprogrammed intermittent speed variation allowing for ventricular and pump washout,[12] the area proximal to the left ventricular outflow tract remains an area of stasis. LVAD-associated shear stresses also activates platelets.[13] Platelets may then attach to adhesion molecules found on the blood-exposed surfaces of the titanium alloys of the device.[14] These activated platelets produce a degree of hypercoagulability. This triad of bioreactive materials, activated platelets and aberrant patterns of flow that produce a thrombogenic environment, further contribute to the increased risk of adverse hemodynamic events. To encourage a stable inflow rheology and reduce the risk of thrombogenicity, optimal positioning of the inflow cannula during surgery is imperative.[15]

The optimal position has been described as angulated towards the mitral valve, parallel to the septum.[16] However, it must be acknowledged that there are many patient characteristics which influence this, including fluid volume status, intraventricular geometry, septal positioning, and remnant contractility. These variables are dynamic and may change once the LVAD has been implanted. For example, the development of right ventricular impairment in some patients following LVAD insertion can contribute to septal bowing, potentially affecting inflow cannula angulation.

The term suboptimal in respect to device positioning relates to deviation from the axis connecting the mitral valve and the ventricular apex, often called the apical axis. Deviation from this axis allows malpositioning to be quantified, with higher angles representing increased deviation from an ideal position. While previous literature has hinted that surgical implant technique may impact the position of the inflow cannula[17,18] there is a paucity of data comparing sternotomy versus thoracotomy. Furthermore, the methodology of measuring the inflow cannula angulation has been reported inconsistently.[13,19,20]

Ideally, the inflow cannula should be parallel to the septum, angled towards the mitral valve.[21] Deviation of the inflow cannula toward the septum or lateral wall may transiently obstruct blood flow due to suction events. This deviation may also increase shear stress and induce turbulent flow patterns, contributing to thrombus formation,[17] as well as potentially higher frequency of mitral regurgitation.[22]

Ventricular re-modeling was previously thought of as irreversible by virtue of the end stage nature of the disease. However, the idea of irreversibility of LV remodeling

has been challenged with studies purporting LVAD induced regression of cellular hypertrophy and normalization of the LV end diastolic pressure–volume relationship, indicating changes in chamber geometry.[23]

However, many studies that report device migration focus on the Heart Mate II which is an intra-abdominal device that displaces and fixes the LV apex inferiorly. This is in contrast to the HVAD and HM III devices which are intrathoracic and therefore concerns of device migration may not be translated to these intrapericardially secured devices.[24]

4.2 | Surgical technique of minimally invasive implantation

In respect to minimally invasive LVAD implantation, several approaches have been previously described[25,26] including the "Hannover" technique involving left thoracotomy and upper mini-sternotomy which was initially described in 2011.[27] At our institution, we favor utilizing two mini-thoracotomy incisions—anteriorly through the right second intercostal space for implantation of the outflow graft and anterolaterally through the left fifth intercostal space for pump implant. A suitable position on the left ventricular apex is determined by dimpling the apex and correlating this position with transoesophageal echocardiography. The outflow graft is then tunneled through to the right anterior thoracotomy incision and sutured to the mid-ascending aorta.

Implanting an LVAD via thoracotomy is more technically challenging and longer cardiopulmonary bypass time may be required for the dissection and tunneling of the outflow graft to the right side of the chest.[28] This may result in a longer cardiopulmonary bypass time and overall operation length. Similarly, peripheral cannulation for cardiopulmonary bypass in the thoracotomy approach can also add to operation duration. However, within our cohort of 14 patients, the first five patients had an average CPB time of 118 min. This is compared to the most recent five patients who had an average CPB time of 99 min. This difference demonstrates the learning curve associated with this procedure and we expect the bypass time, as well as operation time to continue trending down as more procedures are performed.

4.3 | Benefits and limitations of a minimally invasive technique

Sternal sparing approaches to LVAD implantation have been suggested to be associated with several benefits in the intraoperative and postoperative phases. This includes improved visualization,[29] decreased risk of right ventricular failure[30] quicker functional recovery times,[29] and less complications associated with sternal re-entry during transplantation.[31] The two techniques differ in how the left ventricular apex is viewed. In conventional sternotomy, the heart is elevated and rotated whereas the thoracotomy approach allows direct visualization and easier access within the anatomical positioning of the heart. Improved visualization and easier access allows for attachment of the inflow cannula without disturbing the natural anatomical position of the heart.[28] This may also help avoid coronary hypoperfusion that occurs with disruption of the natural cardiac position when handling the heart for inflow cannula insertion during the sternotomy approach.[28]

To avoid full pericardial opening, the heart is only exposed over the left ventricle as well as anterior to the ascending aorta to facilitate pump implant and outflow graft anastomosis. It has been postulated within the literature that this helps to stabilize the right ventricle.[32,33] However, the extent to which this mitigates right ventricular dysfunction in the postoperative period is not clear.[34]

Avoiding a median sternotomy allows for quicker functional recovery and decreased postoperative length of stay.[35] Without the need for sternal precautions, a minimally invasive thoracotomy approach encourages patients to ambulate earlier and participate in less restricted physical therapy, resulting in shorter recovery times.[29] The LATERAL trial reported a decreased length of stay in those implanted via thoracotomy with a mean length of stay of 18 (SD 12) days as compared to the 26-day performance goal of conventional sternotomy patients.[7] While not reaching statistical significance, our thoracotomy cohort demonstrated a similar trend with a median ICU length of stay of 6 days compared to 8 days in the sternotomy group ($p = 0.52$) and a median total postoperative LOS of 25 days versus 32 days ($p = 0.31$).

Sternal preservation is particularly relevant for patients in whom the LVAD is used as a bridge to transplant. In this cohort, sternal preservation is ideal to minimize adhesions and blood loss upon sternal reentry for transplantation.[31] Second, minimizing blood product requirement is an important consideration in this cohort due to increasing sensitization risk prior to transplantation.[36]

While a lateral thoracotomy allows for direct visualization of the apex, the surgeon is limited in their view of, and access to the rest of the cardiac structures. Subsequently, the thoracotomy approach does not allow for concomitant procedures and will not be suitable to all patients.[37] Similarly, in patients who have had previous sternotomies, this approach may not be possible due to the presence of adhesions.

4.4 | Adverse hemodynamic events

LVADs are inherently associated with a variety of hematological derangements including hemolysis, alterations in von Willebrand factor, platelets activation, diminished pulsatility and the need for a high degree of anticoagulation.[38] These factors prime the patient for adverse hemodynamic events including stroke, gastrointestinal bleeding, and pump thrombosis. On top of this, suboptimal LVAD positioning may further contribute to increasing risk based on intraventricular hemodynamics promoting shear stress and platelet aggregation,[13] although this was not evident in our case series.

The LATERAL trial demonstrated that thoracotomy implantation is associated with a decreased adverse event profile compared to conventional sternotomy.[7] More patients made it to transplant or recovery with device explantation free from disabling stroke. However, while there was a significant difference in inflow cannula angles between the sternotomy and thoracotomy groups in the 3D plane, we could not demonstrate a difference in outcomes between the two groups in our study. Several reasons can contribute to this; firstly, despite including all thoracotomies performed at our center, our sample size remains too small to demonstrate a difference. Secondly, duration of support on average prior to transplantation is 1 year at our center. Due to this limited time on pump support, we may not be able to adequately study long term impact.

4.5 | Study limitations

As a single-center study, our sample size is small and the significance of the rates of adverse outcomes may be impacted by this. This may be compounded by our relatively short support times, with most patients being transplanted 1 year after LVAD implantation. While most adverse hemodynamic events such as stroke and gastrointestinal bleeding occur within the first 1 to 2 months,[39] this is a potential limitation when looking at our rates of adverse events as we only included bridging to transplant LVADs as opposed to destination LVAD therapy.

Similarly, we only included patients implanted with HVADs as this was the primary device implanted during the study period. Since this time, the HVAD pump is no longer clinically indicated for use in patients requiring durable mechanical circulatory support. Our center has transitioned to using the HeartMate III (Abbot, Chicago, III). While these devices are similar in that they are intrapericardially implanted, the HeartMate III is larger with a more rigid outflow graft, which may influence device rotation and the potential for migration.

This was a retrospective study, and as such, not all patients had postoperative contrast-enhanced CT which may affect the accuracy of 3D reconstructions and 2D angle measurements. The median time between LVAD implant and CT scan was 49 days. There is little evidence to suggest significant device migration secondary to left ventricular remodeling from chronic unloading,[40] particularly in such a short time frame. However, this is an important factor to consider if measuring devices implanted for longer periods of time.

5 | FUTURE DIRECTIONS

Advancements in cardiac surgery have allowed for a move toward more minimally invasive techniques. Further studies should evaluate the influence of these approaches on device positioning and angulation. Larger scale studies are needed to further assess the impact that device angulation due to surgical incision has on adverse hemodynamic events.

There is a paucity of studies evaluating device malrotation of intrapericardial devices over time. Recreation of serial CT scans to evaluate potential device migration was outside of the scope of this paper. However, this is a potential avenue for future research, using the technique of 3D modeling to measure angulation.

6 | CONCLUSION

A thoracotomy approach is a safe and less invasive method for LVAD implantation and may result in more optimal device positioning due to better visualization during surgery with less deviation of the inflow cannula from the mitral valve. While several methods exist to measure inflow cannula angulation, 3D reconstruction is the most accurate due to a greater appreciation of device positioning compared to 2D images.

AUTHOR CONTRIBUTIONS

Madeleine Pearman: Data collection, drafting manuscript, creation of 3D reconstructions, and angle measurement. Sam Emmanuel: Data collection, statistical analysis, angle measurement, and manuscript review. Paul Jansz: Technical expertise and implantation of ventricular assist devices. Alasdair Watson: Technical expertise and implantation of ventricular assist devices. Mark Connellan: Technical expertise and implantation of ventricular assist devices. Arjun Iyer: Technical expertise and implantation of ventricular assist devices. Sumita Barua: Assistance with data collection and manuscript review. Christopher Simon Hayward: Study design, data analysis, expert opinion, and manuscript review.

CONFLICT OF INTEREST

Paul Jansz and Christopher Simon Hayward have received institutional support and have consultancy agreement with Medtronic, manufacturer of HVAD. None of the other authors have any conflicts of interest in relation to this publication.

ORCID

Madeleine Pearman https://orcid.org/0000-0002-3613-0793
Sam Emmanuel https://orcid.org/0000-0003-1022-1539
Christopher Simon Hayward https://orcid.org/0000-0003-4036-1890

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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