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Article

Patterns of Retrosternal Anatomical Change After LVAD Implantation Using Serial CT Imaging

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Abstract

Background: Left ventricular assist devices (LVADs) are increasingly used as a bridge to transplantation in patients with end-stage heart failure. However, re-sternotomy for heart transplantation carries heightened surgical risk due to retrosternal adhesions involving cardiac structures like the ascending aorta (AA), outflow graft (OFG), and right ventricle (RV). This study aimed to quantitatively describe patterns of anatomical changes in sternal proximity over time and discuss potential patient-level predictors of this change. **Methods:** A retrospective study was conducted at a high-volume cardiac centre, including 101 patients who received HeartWare or HeartMate 3 LVADs via sternotomy between 2013 and 2023. A total of 222 contrast-enhanced CT scans were analysed. Distances from the sternum to the AA, OFG, and RV were measured in the mid-sagittal plane. Mixed-effects regression models assessed longitudinal changes. Univariate regressions explored baseline predictors of anatomical shift within this cohort. **Results:** The AA and RV demonstrated significant reductions, while OFG demonstrated non-significant reductions in distance from the sternum over time ($p = 0.0166$ and 0.000918, respectively). Significant baseline predictors of greater anatomical shift included greater body mass index (BMI) and RV enlargement at the time of LVAD implant for AA, and intra-aortic balloon pump implant for the OFG. **Conclusions:** Serial CT imaging enables longitudinal assessment of retrosternal anatomical changes following LVAD implantation and may assist operative planning prior to heart transplantation. Exploratory univariable analyses identified several patient characteristics associated with greater anatomical change over time. Future prospective multicentre studies, large enough to power multivariate analyses and correlate computed tomography (CT) findings with re-sternotomy outcomes, are required to validate these findings and determine their clinical relevance.

Keywords: LVAD; re-sternotomy; computed tomography; heart transplantation

1. Introduction

1.1 Heart Failure

The global prevalence of heart failure was estimated at 64 million in 2023 [1]. End-stage heart failure patients have an expected mortality of 6–12 months [2]. Heart transplantation remains the gold-standard treatment for end-stage heart failure [3]. The waiting time for heart transplantation varies with donor availability, geographical location and clinical urgency, among other factors, including donor age and comorbidities. The average wait time in the UK for a non-urgent heart transplantation is about 2 years [4]—often longer than the expected survival of patients with end-stage heart failure. This is due to the scarce supply of donor hearts.

1.2 The Role of Durable Mechanical Circulatory Support as a Bridge to Cardiac Transplantation

In recent years, durable mechanical support has been increasingly used as a bridge to transplantation. Patients are typically discharged home after a durable left ventricular assist device (LVAD) implantation, with a significantly improved quality-of-life and a chance to pre-habilitate while awaiting heart transplantation [5].

An LVAD continuously unloads the left ventricle (LV) by redirecting blood from the left ventricular apex and pumping it into the ascending aorta (AA), thereby improving cardiac output, and improving end organ function. The implantable components of LVADs include: (a) the pump head which attaches to the apex of the LV and extracts blood from the LV cavity; (b) the outflow graft (OFG) which is a conduit that inserts into the AA; and (c) the driveline connected to the pump head, which is tunnelled to exit via the abdominal wall and connects to the controller and power supply outside the body.

LVADs can provide significant advantages as a 'bridge to transplant' device compared to medical therapy alone, improving mortality, morbidity, and transplant candidacy [6]. Rates of complications, like thromboembolic events and driveline infections, have declined with the development of newer continuous-flow LVAD models [7]. Although limited to very few case reports, LVAD has enabled myocardial remodelling to the extent that cardiac function has recovered and the LVAD has been explanted without the need for a heart transplant [8]. NICE guidelines encourage a cautious approach to LVAD as destination therapy, which is another seldom used indication for the implantation of a durable LVAD [9].

A durable LVAD may be implanted either through a median sternotomy or a bilateral thoracotomy. In the former approach, heart transplantation is performed through a median re-sternotomy.

Following LVAD implantation, fibrosis and adhesions may cause movement of retrosternal structures towards the sternum in the 'bridge to transplant' period. Alternatively, postoperative inflammatory and exudative processes may transiently increase the distance between the sternum and retrosternal structures [10]. As these processes resolve over time, reductions in sternal proximity measurements may occur independently of true long-term anatomical remodelling or adhesion formation. Structures such as the driveline, the outflow graft, the heart itself and the great vessels are at risk of laceration during re-sternotomy due to their anatomical proximity to the sternum [11,12,13]. Therefore, preparation for a safe re-sternotomy begins at the point of LVAD implantation and has been previously described by Khoshbin et al. [14].

In the context of heart transplantation, intraoperative complications prolong the duration of surgery to halt haemorrhage and repair damaged structures. This increases the cold ischaemic time (CIT)—the time a donor heart would have to be stored in the ice box before being implanted. The Organ Care System (OCS) is a relatively novel development whereby the donor heart is perfused with warm oxygenated blood and is kept beating from explant to implantation. This mitigates donor heart ischaemia and preserves its function until transplantation into the recipient. The OCS is known to be useful in the event of haemorrhage during transplant surgery by preserving the heart for prolonged periods until it can be safely implanted [11]. However, OCS is not yet widely used, so CIT remains relevant. Prolonging the CIT beyond 4 hours is associated with an exponential increased incidence of primary graft dysfunction and higher post-transplant mortality [12,13].

1.3 The Role of Computed Tomography

Computed tomography (CT) imaging plays a crucial role in pre-operative planning for re-sternotomy. It enables thorough assessment of retrosternal anatomy to prevent intraoperative injury to retrosternal structures [15]. The American Society of Echocardiography guidelines recommend the use of CT imaging to monitor mechanical circulatory device (MCS) device position [16], function and infections, while concurrently evaluating thoracic anatomy before heart transplantation. These scans provide an opportunity to evaluate the position of vascular structures in relation to the sternum, so that surgeons can pre-empt risk of injury to structures close to the back of the sternum. For example, in cases where structures are adherent to the back of the sternum, the patient may be placed on femoral cardiopulmonary bypass (CPB) beforehand. This would shrink the heart and hence may reduce the chance of injury to the heart and the structures pressed against the back of sternum [17]. This would also provide haemodynamic stability in an event of an accidental injury.

To assess up-to-date anatomy, conducting a CT with contrast is rarely possible immediately preceding heart transplantation. Donors become available in an unpredictable manner and the effect of contrast on renal function must be considered in patients with heart failure. Therefore, preparatory CT scans must be electively conducted. However, guidelines are ambiguous regarding the optimal frequency and timing of these CT scans whilst patients are awaiting heart transplantation, leading to variation in follow-up protocols between cardiothoracic centres. Patients are often scanned to assess the position or function of LVAD, post-surgical infections, or other complications, particularly early post-implantation. Later CTs may only occur opportunistically in the context of unrelated medical issues, but these scans may be unsuitable for assessing anatomical changes to aid operative planning. It is necessary that protocols are developed to ensure that surgeons have reliable images for the primary purpose of heart transplantation planning.

Ideally, surveillance CT scans would be conducted regularly to produce an accurate anatomical picture for transplant surgeons. However, CT risks include contrast-induced nephropathy, anaphylactic reaction to contrast, and unnecessary radiation exposure. Therefore, unnecessarily frequent CT scans should be avoided. It remains unclear what the optimum frequency of CT scanning should be and will likely need to be tailored to individual patient cohorts.

The purpose of this retrospective study is to identify temporal trends in the proximity of key thoracic structures (at risk of injury during re-sternotomy) to the back of the sternum, in patients with a durable LVAD implanted as a bridge to transplantation. Additionally, the study aims to explore whether baseline patient characteristics were associated with variation in longitudinal retrosternal anatomical change over time in this cohort.

2. Materials and Methods

2.1 Study Design and Patient Selection

All patients who underwent HeartWare or HeartMate 3 LVAD implantation at a high-volume tertiary care centre in northwest London between January 2013 and November 2023 were reviewed. Patients were excluded if LVAD was implanted via a non-sternotomy approach. All CT scans available for each patient during the follow-up period (time from LVAD implantation up to transplant or death) were included. CT scans were excluded if they did not visualise the thorax, were non-contrast, had poor image resolution, or were performed before LVAD implantation or after LVAD explant.

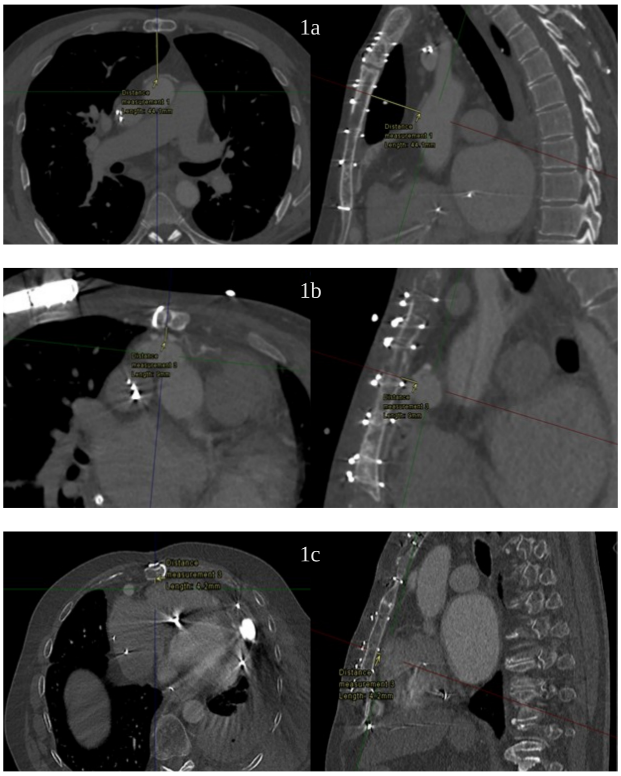

Fig. 1. Computed tomography (CT) images showing distance measured from the posterior surface of the sternum in the midsagittal plane to: (a) the ascending aorta; (b) the left ventricular assist device (LVAD) outflow graft; (c) the right ventricle.

2.2 Measurements

For each CT scan, three sets of measurements were made in the sagittal plane from the posterior surface of the manubrium or sternum about the midline: (1) shortest perpendicular distance to the anterior aortic wall (Fig. 1a); (2) shortest distance to the OFG (Fig. 1b); (3) shortest distance to the RV epicardium (Fig. 1c). Note that the RV here includes the myocardium or any associated coronary vasculature, but not the epicardial fat. The innominate vein was not assessed as it was very proximal or adherent to the sternum in most scans, or poorly visualised. To avoid distortion, measurements excluded regions where vital structures, such as the innominate vein, would be the first to be injured during a midline sternotomy.

To obtain the measurements, the sagittal plane of the CT was adjusted to be in the sternal midline. The coronal plane was adjusted to find the shortest distance from the back of the sternum to the structure in question.

To ensure reproducibility and eliminate inter-user variability, all measurements were made by the researcher, who was trained by a qualified radiologist. All analysis was performed in the bone window setting. The radiologist ensured correct technique and a consistent approach. All CTs were viewed using AGFA Healthcare PACS tools.

Prospectively collected clinical data were stored in the Clinical Data Warehouse or patient record systems and analysed retrospectively.

2.3 Statistical Analysis

All statistical analyses were performed using R version 4.5.0. (R Foundation for Statistical Computing, Vienna, Austria) Missing data were handled via listwise deletion, as implemented by default in R regression functions. A significance threshold of $p < 0.05$ was applied across all analyses. Data normality was assessed using Shapiro-Wilk testing, with parametric data summarised using mean and standard deviation (SD), and non-parametric data summarised using median and interquartile range (IQR).

To visualise individual-level changes in anatomical distances over time, spaghetti plots were generated for each structure of interest (AA, OFG, and RV). These plots displayed both singular and longitudinal measurements for each patient, illustrating intra-patient and inter-patient changes, as well as overall temporal trends. A mixed-effects regression line, accounting for repeated measures within individuals, was superimposed on each plot to represent the average trajectory, with a 95% confidence interval (CI) reflecting uncertainty in the group-level estimate.

Patients were stratified on these spaghetti plots according to the longitudinal behaviour of each structure relative to the midline of the sternum: (1) those who remained in the midline throughout follow-up; (2) those who initially lay outside the midline but subsequently entered it on later scans, and (3) those who began within the midline but exited in subsequent imaging. The midline is significant because sternotomy is performed along the midline of the sternum, so structures in the midline are at risk of injury. Patients were excluded from this analysis if none of the structures in question entered the midline of the sternum in any of their CT scans. Structures <10 mm away from the posterior surface of the sternum were considered at risk of injury from re-sternotomy [18], based on radiological thresholds applied in previous studies.

Changes in anatomical position were defined as the difference in mean CT-measured distances from the sternum to the AA, OFG, and RV, between early post-implantation scans (≤90 days) and later follow-up scans (>1 year). Univariate linear regression analyses were conducted to assess which baseline clinical characteristics predict changes in anatomical positioning. They were done to identify patients who may be more susceptible to anatomical change, thereby requiring enhanced CT monitoring. The twelve baseline variables analysed were: age, sex, ethnicity, body mass index (BMI), history of ischaemic heart disease, diabetes, history of chronic obstructive pulmonary disease, previous intra-aortic balloon pump (IABP), previous sternotomy prior to LVAD implant, LV or RV enlargement (based on echocardiography), and LVAD type (HeartWare or HeartMate 3). These variables were selected based on prior literature identifying them as potential confounders [19]. Categorical variables were summarised with frequency counts per group. For each model, regression coefficients, standard errors, 95% CIs, R^2, and adjusted R^2 values were reported.

Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) were not evaluated, as no formal model selection or comparison between alternative model structures was performed; instead, clinically relevant variables were pre-specified based on existing literature.

3. Results

Descriptive statistics for baseline demographic and clinical characteristics of the study cohort are summarised in Table 1. Overall, 101 patients were included, contributing 222 CT scans.

Table 1. Baseline characteristics of study cohort.

Patient characteristics	Cohort values
Age, mean (SD) [range]	48.5 (12.5) [20–68]
Sex, %	Male, 78 (77.2%) Female, 23 (22.8%)
Ethnicity, %	White, 72 (71.2%) Black, 7 (6.9%) Asian, 9 (8.9%) Unspecified, 13 (12.8%)
BMI (SD) [range]	27.4 (5.5) [17.9–50.2]
LVAD type, %	HeartWare, 83 (82.1%) HeartMate III, 18 (17.9%)
Diabetes, %	Yes, 16 (17.8%) No, 79 (78.2%) Unknown, 6 (4%)
Ischaemic heart disease, %	Yes, 34 (33.6%) No, 62 (61.4%) Unknown, 5 (5%)

Continuous variables are presented as mean (standard deviation) [range]. Categorical variables are expressed as percentages of the total cohort. SD, standard deviation; BMI, body mass index; LVAD, left ventricular assist device.

The number of scans included per patient varied considerably, depending on the follow-up period and the presence of postoperative complications, or other clinical indications for additional CT scans. While 54 patients had just one eligible scan, some had up to 7. The median follow-up duration for CTs was 1071 days (IQR 327–2463). The median time from LVAD implantation to first CT was 73 days (IQR 19–169).

Notably, females were underrepresented in this cohort at 22.8% (Table 1). The mean age was 48.5 years, ranging from 20 to 68 years. Around one-third of patients had a history of ischaemic heart disease.

Note: The distribution of LVAD types reflects practice changes, with only HeartWare devices used prior to 2021 and only HeartMate 3 used from January 2021 onwards due to its clinical superiority [20,21].

Serial CT measurements revealed progressive reductions in the distances between key mediastinal structures and the posterior sternum over time.

The AA demonstrated the most stable positioning, with only one patient entering the midline proximity (n = 100) during follow-up (Fig. 2a). Some patients with OFG to sternum measurements (n = 58) showed transitions into or away from the midline (Fig. 2b). The RV consistently remained in the midline for all patients except one, in whom 182 hyperinflated lungs displaced the heart away from the sternum (Fig. 2c).

A significant decrease in sternum distance over time was observed for the AA and RV, with estimated slopes of −0.002 mm/day (AA: 95% CI −0.004 to 0.000, p = 0.0166; RV: 95% CI −0.004 to −0.001, p = 0.000918) (Table 2). In contrast, the distance between the OFG and the sternum showed a negligible, non-significant change (95% CI −0.003 to 0.002; p = 0.764). Model uncertainty increased at longer follow-up durations because fewer patients contributed longitudinal data at later time points.

Table 2. Change in sternal distance over time.

Structure	Slope	Lower 95% CI	Upper 95% CI	p-value
Ascending aorta	–0.002	–0.004	0	0.0166
Right ventricle	–0.002	–0.004	–0.001	0.000918
Outflow graft	0	–0.003	0.002	0.764

Linear mixed-effects regression models were used to assess the relationship between time and sternal distance for each anatomical structure. The slope represents the estimated change in distance (in mm) per day. A negative slope indicates a reduction in distance over time, while a positive slope indicates an increase. 95% confidence intervals (CIs) are provided to reflect the uncertainty around each estimate. p-values < 0.05 were considered statistically significant.

Across all structures, the 10 mm horizontal line served as a clinical marker for heightened surgical complexity.

The OFG and RV more frequently crossed this critical threshold compared to the AA (Table 3).

The OFG and RV exhibited dynamic changes, with several patients entering or exiting midline proximity and risk zones over time (Table 3). In contrast, the AA remained stable, with negligible changes across follow-up. There was a net increase in the number of patients who entered the risk threshold for all structures through follow-up. RVs most frequently breached the risk threshold, with 31 (70.4%) patients with longitudinal scans available crossing below it at some point during follow-up. In contrast, only 14 (24.1%) and 3 (3.0%) patients exhibited changes in OFGs and AAs respectively.

A total of 52 patients underwent CT imaging within the immediate post-implantation period (≤90 days), while 35 patients had follow-up scans performed beyond one year

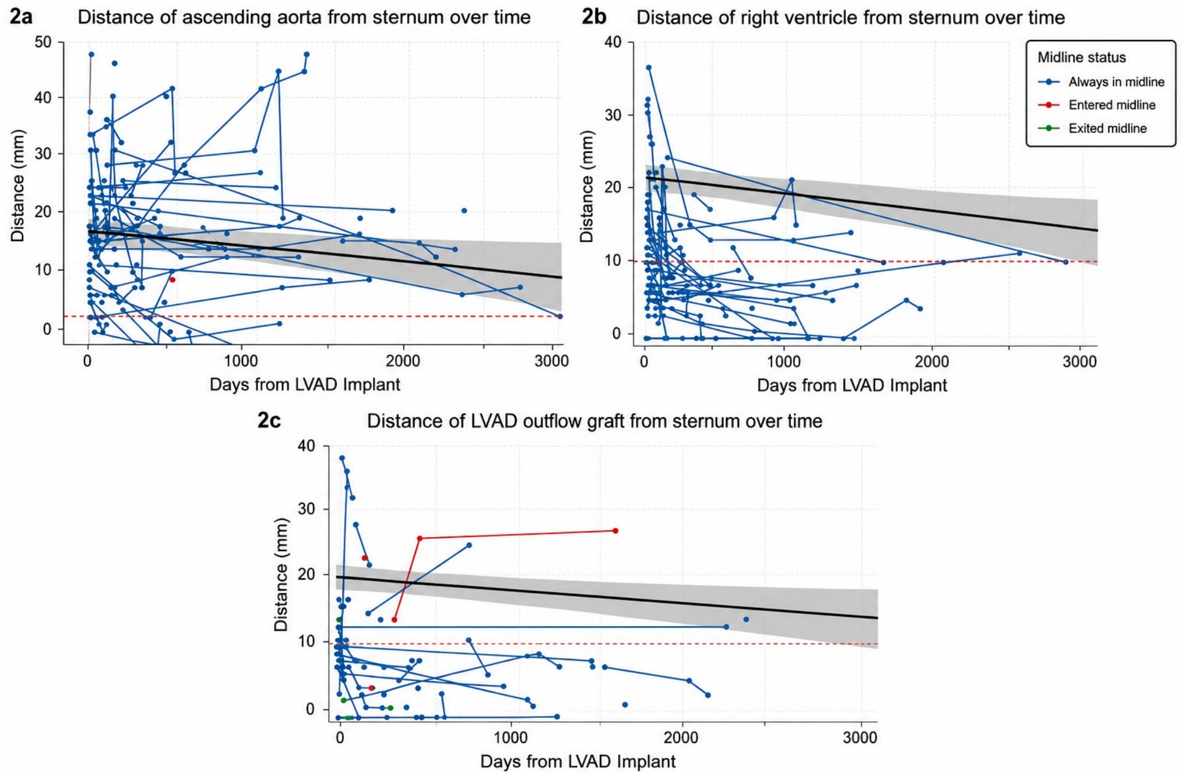

Fig. 2. Spaghetti plots with each line representing a single patient's serial CT measurements of the distance between the: (a) Ascending aorta; (b) Right ventricle; (c) LVAD outflow graft, and the posterior aspect of the sternum. The red dashed horizontal line at 10 mm represents the surgical risk threshold. The patients shown in red were observed to transition from being out of midline (not measurable) to in-line with the sternotomy path. The patients shown in green were observed to transition from being in the midline to being out of the midline. All other patients are shown in blue. The solid black line represents the group-level trajectory estimated using a mixed-effects regression model with a random intercept for each patient, and the shaded grey band denotes the 95% confidence interval of the model's fixed-effect estimate, based on standard error around the mean. Abbreviations: CT, computed tomography; LVAD, left ventricular assist device.

Table 3. Longitudinal behaviour of mediastinal structures relative to the sternum in LVAD patients with serial CT imaging.

Measurement	Patients in midline at any point	Patients with serial measurements	Patients who entered midline	Patients who exited midline	Patients who entered risk threshold	Patient who started and remained under risk threshold	Patients who exited risk threshold
Ascending Aorta to Sternum	100	46	1	0	3	0	0
Outflow graft to sternum	58	24	3	4	5	9	2
Right Ventricle to Sternum	95	44	0	1	10	21	2

Patients were stratified based on the positional dynamics of the ascending aorta, outflow graft, and right ventricle over time. Columns show the total number of patients (with serial measurements) per structure, the proportion who entered or exited the midline during follow-up, and the number crossing a predefined surgical risk threshold of <10 mm sternum distance. "Entered midline" refers to patients whose structures encroached toward the midline on later scans after initially lying outside of it. "Exited midline" reflects structures that shifted away from the midline after initially being in line with it. Similarly, patients entering or exiting the <10 mm risk threshold were noted.

after LVAD implantation. Assessment of temporal changes in sternal distances required paired imaging from both time-points. Accordingly, longitudinal analysis of sternal distance changes was feasible in 14 patients who had both early (≤90 days) and late (>1 year) CT scans available.

Baseline characteristics that significantly predicted a greater reduction in sternal distance from the AA were the presence of RV enlargement at the time of LVAD implantation, which was associated with a 7.5 mm greater decrease in distance (p = 0.0429, R^2 = 0.350), and increasing BMI, which predicted a 0.68 mm greater reduction (p = 0.0457, R^2 = 0.361) (Table 4, **Supplementary Table 1**). In addition, a positive history of previous sternotomy was associated with a 10.11 mm lesser decrease in distance (p = 0.0374, R^2 = 0.398), while the female sex predicted a 7.61 mm lesser reduction (p = 0.0289, R^2 = 0.307).

Table 4. Univariate regression analysis.

Structure	Predictor	Estimate	Lower 95% CI	Upper 95% CI	*p*-value
Ascending aorta	Sex	–7.16	–14.28	–0.94	0.029
	BMI	0.68	0.02	1.35	0.046
	Previous sternotomy	–10.11	–19.49	–0.74	0.037
	RV enlargement	7.5	0.29	14.71	0.043
Outflow graft	Previous IABP	8	1.67	14.33	0.023
Right ventricle	Previous IABP	–9.25	–17.35	–1.15	0.029

Significant predictors identified from the univariate regression analysis evaluating associations between baseline demographic and clinical characteristics and changes in CT-measured sternal distances during LVAD support. The outcome for each model was the change in distance from the posterior sternum to the ascending aorta, outflow graft, or right ventricle, calculated as the difference between early post-implant CT scans (≤90 days) and those obtained beyond one year. Only predictors reaching statistical significance ($p < 0.05$) are shown. The table reports the regression coefficient (estimate), 95% confidence interval (CI), and *p*-value for each significant variable. Abbreviations: BMI, body mass index; RV, right ventricle; IABP, intra-aortic balloon pump; CT, computed tomography; LVAD, left ventricular assist device; CI, confidence interval.

The presence of a previous IABP was associated with an 8 mm greater reduction in the distance between the OGF and sternum in a model with a relatively high fit ($p = 0.0227$, $R^2 = 0.678$), indicating a substantial anatomical shift in these patients (Table 4, **Supplementary Table 1**). Conversely, prior IABP use also predicted a 9.25 mm lesser reduction in the distance from the RV to the sternum ($p = 0.0285$, $R^2 = 0.340$), suggesting that while OFG proximity increased more markedly, RV proximity decreased to a lesser extent. IABP use was the only variable that significantly predicted distance changes in both structures.

Only predictors with statistically significant associations are presented in Table 4. The full univariate regression results for all predictors are provided in **Supplementary Table 1**.

4. Discussion

4.1 Retrosternal Structures Move Closer to the Sternum Over Time

This study supports existing literature suggesting that retrosternal anatomical relationships may change following sternotomy and provides a quantitative longitudinal assessment of the proximity of three key thoracic structures to the posterior sternum in LVAD patients. While the observed rates of change were modest and should be interpreted cautiously, these findings offer preliminary descriptive data regarding retrosternal anatomical dynamics during the ‘bridge to transplant’ period.

Following LVAD implantation, postoperative inflammatory and exudative processes may transiently increase the distance between the sternum and retrosternal structures in the early recovery period [10]. As many of the initial CT scans in this cohort were obtained during this postoperative phase, reductions in sternal proximity measurements over time may occur independently of true long-term anatomical remodelling or adhesion formation, highlighting the need for prospective studies with protocolised imaging intervals to better distinguish these processes. Nonetheless, the mixed-effects regression models still demonstrate measurable longitudinal changes in retrosternal anatomical relationships over time within this LVAD cohort and the importance of CT follow-up post-LVAD implantation.

4.1.1 The Outflow Graft and Right Ventricle

The proximity of the OFG and the RV to the sternum is already a well-established limiting factor for safe re-entry. Surgeons have adapted techniques during LVAD implantation to mitigate the future risk of injury during resternotomy. The OFG was found to be below the 10 mm risk proximity in 45.8% of patients from their very first scan, potentially explaining the absence of a statistically significant rate of change over the follow-up period.

Current practice focusses on creating a physical barrier between the OFG (and concurrently the RV) by placing a Gore-Tex sheet or fashioning a polytetrafluoroethylene or “graft-on-graft” covering [22], both to protect structures from damage and prevent the formation of adhesions which reduce proximity over time. Gore-Tex placement is a surgical practice utilised at this cardiac centre and could explain why the regression of OFG distance from the sternum over time is non-significant, since Gor-Tex is effective in preventing adhesions in some of these patients. This study provides evidence to suggest that additional measures should be sought during LVAD implantation to protect retrosternal structures.

The statistically significant shift of the RV towards the sternum could hypothetically be because of the increased risk of RV enlargement secondary to the sequela of LVAD implantation. Meta-analysis shows that 35% of patients on LVAD develop right ventricular failure (RVF) post-LVAD implant [23], due to the increased cardiac output from the pump increasing venous return and causing RV dilation [24]. RVF can develop at any point throughout the ‘bridge to transplant' period [23]. This theory is purely speculative until future studies collect clinical and echocardiographic data suggestive of RVF, tricuspid and aortic insufficiency concurrently to CT-measured distances of the RV from the sternum. These could include size metrics such as RV basal diameter, as well as functional parameters such as tricuspid annular plane systolic excursion (TAPSE). Clinically, findings of a positive association between echocardiographic metrics and sternal distance could recommend further CT imaging following diagnosis of RVF.

There may also be an element of selection bias regarding RV movement towards the sternum, as patients with RV failure and associated RV distension may have been more likely to undergo CT follow-up imaging, potentially exaggerating the observed reduction in RV-to-sternum distance over time.

4.1.2 The Ascending Aorta

An enlarging AA may also shift closer to the sternum. In the context of LVAD, aortic dilation may be secondary to a larger inferior angle between the OGF and AA at the level of insertion. This could be due to aortic wall sheer stress exacerbated by blood rushing into the AA from the OFG at a more perpendicular angle [25]. Despite this, the AA was adherent to the sternum in none of these patients, and only 3% of AAs entered the risk threshold throughout follow-up. Yamauchi et al. [26] conducted re-sternotomies on patients with and without direct vessel adhesion to the sternum. Vessel injuries only occurred in the presence of direct adhesion to the sternum, regardless of the proximity of vessels to the sternum. 10% of their patients had aortic adherence on preoperative CT scanning, indicating that the occurrence is not uncommon and that this study does not capture such cases.

Nonetheless, this study demonstrated via mixed-effects regression that there was a significant increase in proximity of the AA to the sternum over time. Therefore, surgical techniques like those used to shield the OFG or RV from re-sternotomy injury should be developed to protect the AA.

4.1.3 Future Directions for Mapping Temporal Changes

Considering all scans made after 1 year of LVAD implantation to be adequate, long-term follow-up is a somewhat arbitrary assumption. There is no universal or precise answer as to when retrosternal structures anatomically stabilise after sternotomy, as this is largely determined by post-operative complications. Although infections, haematomas and effusions may resolve much sooner, sternal stabilisation takes several months [10]. It is unknown exactly when the AA, OFG and RV stop progressing closer to the sternum. Segmenting the follow-up into smaller time categories over which changes in sternal distance can be measured could determine the timepoint at which anatomical changes slow down and the frequency of CT follow-up can be reduced. To minimise uncertainty and robustly power mixed-effects regression models, future studies should involve more patients with long-term post-LVAD CT imaging so that more measurements can be compared.

The patients in this cohort were on LVAD for an average of nearly 3 years. It would therefore have been valuable to conduct univariate analyses on distance changes from the sternum within a longer-term follow-up period, for example, by comparing changes between the routine scan taken 1-year post-implant at this centre and scans taken around 3-years. Unfortunately, there were not enough patients with multiple scans beyond 1-year to meaningfully analyse, but future studies with larger sample sizes could enable this analysis.

4.2 Potential Predictors of Greater Anatomical Momentum Towards the Sternum

Univariate regression models identified several significant predictors influencing the change in AA distance over the follow-up period in this cohort. Being female significantly decreased the change in distance towards the sternum, likely due to the smaller thoracic anatomy in females having less capacity for change. However, the underrepresentation of females in this cohort may reduce the reliability and generalisability of sex-based findings.

Patients with a higher initial BMI had greater potential to lose weight because of LVAD. Improvements in cardiac function and cardiac output would reduce fluid retention and improve patient exercise tolerance, enabling them to lose fat, working to reduce the space between the sternum and AA. Additionally, end-stage heart failure patients may suffer from cardiac cachexia, with low BMIs, may gain substantial amounts of tissue as they improve with LVAD [27], thereby reducing their risk of cardiac injury during re-sternotomy by pushing structures away from the sternum.

It is worth noting that the accuracy of BMI data at the start of follow-ups may not stay accurate throughout, as patients tend to drop BMI category during the 'bridge to transplant' thanks to better mobility following discharge with durable LVAD [28]. Future studies should instead rely on BMI measured concurrently with the follow-up CT imaging being analysed.

Previous sternotomy before LVAD implant also emerged as a significant predictor of decreased movement of AA distance towards the sternum, yet there is known to be a heightened risk of cardiac injury during second re-sternotomy [29]. This suggests that cardiac structures were already close to the sternum in patients with sternotomy prior to LVAD implant re-sternotomy. The bulk of the movement towards the sternum of the AA could have occurred after the previous sternotomy but before LVAD implant, explaining this association.

Existing RV failure was also a significant predictor of greater anatomical change. Progressive RV dilation, tricuspid regurgitation, and aortic valve insufficiency during LVAD support may alter cardiac geometry and contribute to increased proximity or adhesion of mediastinal structures to the sternum over time. Interestingly, prior IABP support before LVAD implantation was associated with a greater change in OFG distance but a lesser change in RV distance from the sternum, potentially reflecting differences in baseline RV function or postoperative RV remodelling in these patients. However, detailed longitudinal echocardiographic and haemodynamic assessment was beyond the scope of the current study, and these interpretations remain speculative. Future studies incorporating serial echocardiographic RV parameters, valvular assessment, and heart failure severity may help clarify the relationship between postoperative cardiac remodelling and re-sternotomy risk.

An elevated R^2 value in these univariate analyses suggest an overfitting of the model, limited sample size and failure to remove confounders. These findings should be interpreted cautiously. Validation in larger prospective studies could support specific CT surveillance recommendations.

4.3 Further Limitations and Future Directions

4.3.1 Using Gated CT-Scans

ECG-gated CT imaging synchronises image acquisition with specific phases of the cardiac cycle, thereby reducing variation in cardiac chamber dimensions and motion between scans. This is particularly relevant when measuring sternal proximity, as the distance between the sternum and dynamically contracting structures such as the RV may vary between systole and diastole. This study used non-ECG-gated CT scans, which may not fully account for cyclical changes in ventricular size and proximity to the sternum throughout the cardiac cycle. Nonetheless, gross anatomical changes in distance from the sternum, as shown by the mixed-effects regression models (Fig. 2a–c), remain valid. Any phase-related variability would only introduce random measurement noise rather than systematically bias gross measurements toward reduced sternal proximity over time.

4.3.2 Stratifying by Aetiology

The ages and comorbidities of the patients varied greatly, suggesting that the causes of end-stage heart failure could range from hypertrophic to ischaemic cardiomyopathy. Stratifying based on aetiology was not possible due to sample size restraints.

4.3.3 Diversity Across Centres

The mean duration on LVAD as a bridge to transplant for these patients was 936 days, however cardiac centres across the UK show substantial variability on this metric, with ‘bridge to transplant’ times ranging from 517 to 2230 days [4]. This challenges the generalisability of the findings from the current cohort, as institutional differences in transplant timing may significantly influence sternal distance.

4.3.4 Need for Larger Cohorts and Multivariate Analysis

The relatively small number of patients with paired longitudinal CT imaging limited the statistical power of this study, particularly for regression modelling. Consequently, only exploratory univariate analyses were performed, which do not account for interactions or confounding relationships between clinical variables. The associations identified should therefore be interpreted cautiously and considered hypothesis-generating rather than independently predictive. A larger cohort of patients with serial imaging would enable adequately powered multivariate modelling to determine specific patient characteristics independently associated with greater retrosternal anatomical change over time. This would substantially aid the development of guidelines for focused CT monitoring patients with these characteristics.

4.3.5 Identifying a Risk Threshold

Due to the niche nature of patients who go on to have re-sternotomy-related transplant complications, this study could not correlate CT-measured sternal distances with operative complications during re-sternotomy. Larger studies with a greater pooled incidence of re-sternotomy complications could identify clinically meaningful risk thresholds at which the incidence of intraoperative injury begins to increase and thus improve the predictive utility of preoperative CT assessment. They would also help generate guidelines surrounding surveillance and operative planning strategies.

4.3.6 Stratifying by LVAD Device

HeartWare devices, which made up the majority of devices used in this study, are no longer in clinical use. HeartWare and HeartMate 3 devices differ significantly in terms of their pump configuration, outflow graft dimensions, and mediastinal positioning, which may influence postoperative anatomical relationships and proximity to the sternum.

Compared with HeartWare devices, the HeartMate 3 utilises a larger 14 mm outflow graft and bend relief, which may contribute to greater compression between the right ventricle and sternum, particularly in smaller patients or those with RV dilation. Surgical factors such as graft routing, graft angulation, and aortic anastomosis position may also influence retrosternal anatomy and re-sternotomy risk.

Due to a relatively small number of HeartMate 3 patients in this cohort, combined with shorter follow-up duration due to a later implantation era, meaningful device-specific subgroup analysis was not possible. Data primarily from HeartWare devices should be extrapolated to contemporary devices with great caution. Larger contemporary cohorts consisting predominantly of HeartMate 3 patients would help determine whether device-specific differences in retrosternal anatomical movement exist.

4.3.7 Including Paediatric Populations

An additional limitation of this study is the exclusion of paediatric and adolescent patients, as the cohort was derived from an adult tertiary cardiac centre. Anatomical changes following LVAD implantation may differ significantly in younger or smaller-bodied patients due to their ongoing growth. Since there are no specific paediatric LVAD devices, current HeartMate 3 and HeartWare devices occupy a relatively large mediastinal footprint in this population, potentially putting paediatric patients at greater risk of injury due to a greater sternal proximity of their mediastinal structures. Future studies involving paediatric and congenital heart disease centres may help determine whether surveillance imaging strategies should differ according to patient age and body size.

4.4 Clinical Application

This study highlights the potential value of serial CT imaging in characterising longitudinal retrosternal anatomical change following LVAD implantation. At the centre where this study was conducted, these findings have prompted the introduction of routine annual ECG-gated CT surveillance in durable LVAD patients awaiting heart transplantation, to improve reproducibility of sternal proximity measurements by eliminating variability related to cardiac motion throughout the cardiac cycle.

The rationale for this practice change is to ensure that transplant surgeons have more standardised and up-to-date anatomical imaging available during operative planning for re-sternotomy. Serial imaging can help identify progressive proximity of retrosternal structures to the posterior sternum, which may influence surgical preparation, cannulation strategy, or consideration of peripheral cardiopulmonary bypass prior to sternal re-entry.

Further prospective studies incorporating protocolised ECG-gated imaging and correlation with intraoperative outcomes are required to determine whether routine longitudinal CT surveillance improves operative safety or clinical outcomes in this patient population. This was not possible in our cohort due to a very low incidence of intra-operative complications associated with re-sternotomy.

4.5 Surgical Tips and Tricks

The importance of prior surgical and contingency planning has previously been described by Khoshbin et al. [14]. In summary, preparation for LVAD explantation and heart transplantation begins at the time of LVAD implantation. The authors advise positioning the driveline and outflow graft away from the posterior sternum and midline during their course to the ascending aorta. Protective measures, such as an inferior pericardial shelf and placement of a Gore-Tex membrane between the right ventricle, aorta, and posterior sternum, are also effective in reducing adhesions and re-sternotomy risk. Other centres also report using an expanded polytetrafluoroethylene at the time of LVAD implant [30].

In the authors' experience, bilateral thoracotomy approaches may make re-sternotomy comparably safe to first-time sternotomy by minimising retrosternal adhesions following LVAD implantation. This approach also preserves the option for temporary right ventricular support if required. Although concomitant valvular procedures may theoretically reduce postoperative RV dysfunction and RV dilatation, current evidence has not consistently demonstrated a reduction in RV failure following LVAD implantation, and routine use for this indication remains controversial [31].

5. Conclusions

This study identifies dynamic changes in retrosternal anatomy post-LVAD implant, by quantifying the rate of change in proximity of the ascending aorta, LVAD outflow graft and RV to the posterior sternum at the midline. This brings quantitative novelty to the literature and reinforces the importance of CT follow-up in the 'bridge to heart transplant' period for assessing re-sternotomy risk at the time of heart transplantation. Exploratory analyses identified 5 routinely collected patient characteristics associated with greater retrosternal anatomical change over time, in this cohort – these findings require validation in larger prospective cohorts. Future prospective multicentre studies with protocolised ECG-gated imaging and operative outcome correlation may enable more robust assessment of longitudinal anatomical trends, confounding factors, and generalisability across diverse surgical practices.

Availability of Data and Materials

The datasets supporting this study are not publicly available due to institutional restrictions on sharing patient-level clinical imaging data. Access may be granted to qualified researchers upon reasonable request and with appropriate data-sharing agreements in place.

Author Contributions

AS and EK designed the research study. AS, SY, SR, RI and SM performed data curation and investigation. AS, SY, SR, RI, SM, YS and EK contributed to the study methodology and validation of the findings. AS, YS and EK performed the formal analysis. AS and EK managed project administration and resources. AS and EK contributed to data visualisation. AS, SR and EK prepared the original manuscript draft. All authors contributed to manuscript review and editing, critically revised the manuscript for important intellectual content, read and approved the final version of the manuscript, participated sufficiently in the work to take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

The study was conducted in accordance with institutional guidelines and the principles of the Declaration of Helsinki. This retrospective study was conducted using routinely collected clinical and imaging data. According to Guy's and St Thomas' NHS Foundation Trust's policy, formal ethics committee approval and informed consent were waived for this retrospective service evaluation/audit study involving anonymised data and no direct patient intervention.

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Conflicts of Interest

The authors declare no conflicts of interest.

Declaration of AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work the authors used ChatGpt-4.0 to help structure sections of this manuscript. After using this tool, the authors reviewed and edited the output and take full responsibility for the content of the publication.

Supplementary Material

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.31083/HSF50771.

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