# Left Ventricular Assist Device Outflow Graft Compression: Incidence, Clinical Associations and Potential Etiologies

CORY R. TRANKLE, MD,[1] JOHN D. GRIZZARD, MD,[2] KEYUR B. SHAH, MD,[1] LEILA REZAI GHARAI, MD,[2] FRANKLIN DANA, MD,[2] MATTHEW S. KANG, BS,[3] ANDREW E. ANDREAE, BS,[3] KEVIN DESAI, BS,[3] MOHAMMED A. QUADER, MD,[4] AND ZACHARY M. GERTZ, MD[1]

*Richmond, USA*

**ABSTRACT**

**Background**: Left ventricular assist devices (LVADs) have revolutionized the treatment of advanced heart failure, but proliferation of device therapy has unmasked potential complications. Reports have emerged of outflow graft narrowing due to extrinsic compression.

**Methods and Results**: The records of patients with LVADs that had been implanted at our institution were reviewed. Those who had postimplantation computed tomography angiographies sufficient to analyze the outflow graft lumen were identified, and the studies were analyzed to characterize the outflow graft lumen. We identified 241 patients; 110 (46%) had suitable computed tomography angiographies. Of those, 15 (14%) had evidence of outflow graft lumen narrowing, all in HeartMate devices and all within the portion covered by the bend relief. Of the 15, 3 underwent invasive examination, all without intraluminal thrombus but, rather, with biodebris between the bend relief and the outflow graft. Patients with HeartWare devices had a wide range of biodebris accumulation surrounding the outflow graft but no cases of lumen narrowing. On multivariable analysis, 1) time from device implant to scan, 2) nonischemic cardiomyopathy and 3) age at implant were significantly associated with higher risk of graft narrowing.

**Conclusion**: Outflow graft narrowing can be seen in a number of patients with HeartMate LVADs within the portion covered by the bend relief. In the limited number of patients who underwent invasive evaluation, the narrowing was found to arise from extrinsic compression rather than intraluminal thrombus. The clinical significance of this requires further investigation. (*J Cardiac Fail 2019;25:545–552*)

**Key Words:** Heart failure, heart-assist devices, graft occlusion, vascular, computed tomography angiography.

## Introduction

Heart failure (HF) is highly prevalent, affecting about 5.7 million people in the United States and at least 26 million worldwide.[1,2] Left ventricular assist devices (LVADs) have revolutionized the treatment of many patients with end-stage HF, extending life as either a bridge to transplantation or as a destination therapy. But, as with any new technology, large clinical trials and real-world experience have elucidated many potentially life-threatening complications.[3–5] Recently, the United States Food and Drug Administration issued a recall related to LVAD outflow graft complications.[6]

Computed tomography angiography (CTA) is a valuable diagnostic tool when LVAD outflow graft complication is suspected, such as graft kinking or narrowing.[7,8] However, due to the metallic composition of pump hardware and finite spatial resolution at the borders of cannula components, CTA can have difficulty in determining certain aspects of the LVAD, including the position of the outflow graft material. This can be important because different etiologies of outflow graft obstruction (eg, intraluminal thrombosis, graft kinking, anastomotic stenosis, extrinsic compression) can have divergent treatment strategies. We recently published a case from our institution in which CTA demonstrated LVAD outflow graft narrowing that appeared to be consistent with intraluminal thrombus, but which was later found by intravascular ultrasound (IVUS) to be extrinsic compression resulting from biodebris buildup within the bend relief. The patient was treated with stenting rather than increased anticoagulation or thrombolytics.[9]

*From the [1]Division of Cardiology, VCU Pauley Heart Center, Virginia Commonwealth University, Richmond, Virginia, USA; [2]Department of Radiology, Virginia Commonwealth University, Richmond, Virginia, USA; [3]School of Medicine, Virginia Commonwealth University, Richmond, Virginia, USA and [4]Division of Cardiothoracic Surgery, VCU Pauley Heart Center, Virginia Commonwealth University, Richmond, Virginia, USA.*

Manuscript received January 1, 2019; revised manuscript received March 13, 2019; revised manuscript accepted May 4, 2019.

Corresponding Author: Zachary M. Gertz, MD, VCU Pauley Heart Center, 1200 East Broad Street, Box 980036, Richmond, Virginia 23298. E-mail: zachary.gertz@vcuhealth.org

Conflicts of interest: K.S. has served as a consultant for Medtronic, Syncardia, Akcea, and Alnylam.

Funding: None.

1071-9164/$ - see front matter

© *2019 Elsevier Inc. All rights reserved.*

https://doi.org/10.1016/j.cardfail.2019.05.004

There are limited data in the literature to inform clinicians how to interpret LVAD outflow cannula narrowing when detected by CTA, a finding that is often assumed, by default, to be intraluminal thrombus.[10] We hypothesized that biodebris buildup within the bend relief, causing graft compression, might be a more common scenario than is currently recognized. So we conducted a retrospective study of patients with LVADs who had undergone CTA of the chest in order to achieve better understanding of the incidence, associated clinical factors (which might provide insight into the mechanism) and clinical consequences of outflow graft narrowing with this appearance.

## Methods

The Virginia Commonwealth University Institutional Review Board approved the study protocol.

### Study Population

The medical records of patients who received LVADs between May 2009 and December 2017 at our institution were reviewed to determine whether they had undergone CTAs of the chest at any time following LVAD implantation. Those in whom a CTA was performed with contrast bolus timing sufficient to examine the outflow graft were further analyzed; all other patients with LVADs served as a comparison group.

### Imaging Analysis

The CTA images of the outflow cannulas were analyzed by 3 cardiothoracic imaging specialists (LRG, FD, JDG). Because of the differences in design, it was necessary to assess the HeartMate II and HeartMate 3 models (Abbott, Chicago, Illinois) differently from the way we assessed the HeartWare HVAD (Medtronic, Minneapolis, Minnesota) model.

The HeartMate model incorporates a bend relief structure at the proximal portion of the outflow graft to prevent graft kinking. It has a 21 mm internal diameter in the HeartMate II and an 18 mm diameter for the HeartMate 3. The bend relief is a ribbed Gore-Tex tube, 4 inches long in both models, and it is impervious to blood. Within this bend relief is the sealed outflow graft, which measures 14 mm in diameter in both models but is expected to expand to some degree once exposed to LVAD flow and aortic blood pressure.[11,12] Hence, in HeartMate II and HeartMate 3 models, there is a 3.5 mm and a 2 mm circumferential space (7 mm and 4 mm aggregate diameters), respectively, between the outflow graft and the inner surface of the bend relief tube before any graft expansion.

Alternatively, the HeartWare strain relief is made of plastic rings with snap joints that afford flexibility to the proximal outflow graft and allow blood or debris to seep out between the rings. The ring diameter matches the outflow graft diameter (10 mm), which precludes any space between the strain relief and outflow graft.[13]

With these differences in mind, HeartMate models were examined at the level of the bend relief, measuring the maximal aggregate biodebris length within any 1 diameter, with the understanding that it was not always evident whether this biodebris was within the outflow graft (ie, thrombus) or external to it (ie, buildup of material between the bend relief and outflow graft). If this diameter of biodebris was found to reach $\geq$ 7 mm in the HeartMate II or $\geq$ 4 mm in the HeartMate 3 (resulting in an expected minimum outflow graft diameter of $\leq$ 14 mm), further analysis was performed to determine the minimal area of the outflow graft inner lumen. The remainder of the outflow graft distal to the bend relief was also examined, and any luminal narrowing or occurrences of kinking were recorded, including in the body of the graft and at the aortic anastomosis site.

In contrast, because the HeartWare devices did not have interluminal spaces to analyze, the amount of biodebris buildup around the outflow cannula was inspected in all scans. To facilitate comparison with HeartMate devices, any outflow graft luminal narrowing (to $\leq$ 10 mm diameter) or any aggregate biodebris accumulation of $>$ 4 mm in any single cross-sectional view of the outflow cannula underwent measurement of the minimal outflow cross-sectional luminal area. In cases in which more than 1 CTA was available to measure, the study that had the most severe outflow graft narrowing was included in the analysis.

The scans evaluated in this patient cohort were obtained on a 64-slice CT scanner (Somatom Definition 64, Siemens Medical Solutions, Malvern, Pennsylvania) in our radiology department. Scanning parameters included a detector thickness of 0.6 mm, a section thickness of 0.75 mm, a reconstruction interval of 2 mm and, typically, 120 kVp and 120-200 mAs. The studies were performed with intravenously administered contrast media: Omnipaque 350, Isovue 370 or Visipaque 320 (GE Healthcare, Princeton, New Jersey), depending on the patient's renal function and the absence of contraindications. Between 80 and 120 mL of contrast media were administered at a rate of 4 mL/sec. Proper timing to reach optimal arterial enhancement was achieved primarily through standard timing delays of 25 to 30 seconds. Bolus chasing or a test bolus was sometimes employed as an alternative.

### Clinical Data

Clinical data at the time of LVAD implant, including patient demographics, type of device, implant status (bridge to transplant vs destination therapy), and cardiomyopathy type (ischemic vs nonischemic), were recorded for all patients. In the patients who had a CTA to analyze, additional information was recorded at the time of the scan, including reason for scan, time since device implantation, anticoagulation strategy, and laboratory data. Clinically significant outcomes, such as death, transplant, device (complete or partial) exchange or intervention, and clinical diagnosis of pump thrombosis, were also documented.

### Statistical Analysis

Descriptive summaries of continuous measurements are expressed as mean ± SD or median and interquartile range for parametric or nonparametric data, respectively. Descriptive summaries of categorical data are expressed as frequencies and proportions. The Student t test or the Mann-Whitney U test was used to compare baseline characteristics between continuous normally and non-normally distributed variables, respectively, and the Fisher exact test was used to compare categorical variables. Event rates were compared using the log-rank test. Binary logistic regression with backward selection was used to identify those variables having significant association with outcomes. The exact logistic regression model was considered due to the relatively small number of events. The discriminating ability of the binary logistic regression model was assessed by using the area under the ROC curves (AUC or c-statistic), and the bootstrap method was implemented to evaluate how the estimated model would perform in future subjects. A 2-sided $P$ value of $< 0.05$ was considered statistically significant. All analyses were conducted using SPSS v 25.0 (IBM, New York, New York) and SAS 9.4 (SAS Institute, Cary, North Carolina). For comparisons among patients with CTAs to analyze, events of interest were death as well as a composite of death and LVAD intervention (device exchange or stenting within the graft) and were analyzed from the time of the scan.

## Results

### Baseline Characteristics

Patient identification and inclusion in the analysis are shown in Figure 1. We identified 241 patients who had an implanted LVAD within the specified timeframe, of whom 110 (46%) had a CTA study with contrast bolus timing suitable for analysis of the outflow graft. Reasons for exclusion were primarily no scan (n = 72) or noncontrasted studies (n = 49). Baseline characteristics are summarized in Table 1. Compared to patients with no CTA to analyze, those with CTAs had higher rates of ischemic cardiomyopathy and were more likely to have had a HeartMate device (Heartmate II or HeartMate 3) implanted. After censoring the first 14 days following device implant (to account for early postoperative mortality), patients who had CTAs available to analyze had similar rates of survival compared to those with no CTAs to analyze ($P = 0.82$).

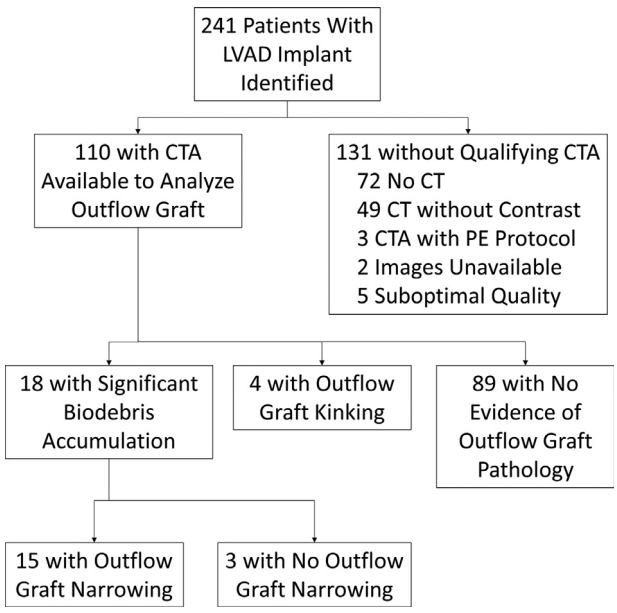


**Fig. 1.** Study flow chart. CT, computed tomography; CTA, computed tomography angiography; LVAD, left ventricular assist device; PE, pulmonary embolism.

**Table 1.** Clinical Characteristics at the Time of Device Implant

| | CTA (N = 110) | No CTA (N = 131) | $P$ value |
|---|---|---|---|
| Age at implant (years) | 52.9 ± 13.7 | 55.3 ± 13.3 | 0.95 |
| Gender, male | 79 (72%) | 96 (73%) | 0.89 |
| Race, white | 53 (48%) | 71 (54%) | 0.37 |
| Status | | | 0.70 |
| Bridge to transplant | 45 (41%) | 57 (44%) | |
| Destination therapy | 65 (59%) | 74 (57%) | |
| Body mass index ($m^2$/kg) | 30.0 ± 7.3 | 30.0 ± 6.9 | 0.42 |
| Body surface area ($m^2$) | 2.1 ± 0.3 | 2.1 ± 0.3 | 0.63 |
| Etiology of cardiomyopathy | | | 0.03 |
| Ischemic | 34 (31%) | 59 (45%) | |
| Nonischemic | 76 (69%) | 72 (55%) | |
| Device | | | 0.04 |
| Heartmate device (HM II or HM 3) | 93 (85%) | 96 (73%) | |
| HeartWare HVAD | 17 (15%) | 35 (27%) | |
| Time from device implant to scan (days) | 464 ± 557 | – | – |

CTA, computed tomography angiography; HM, HeartMate.

### Computed Tomography Measurements

The imaging analysis approach as described in the Methods section is summarized in Figure 2. All patients with HeartMate devices had some degree of biodebris within the bend relief; there were 15 patients in whom this biodebris was associated with outflow graft luminal narrowing. This represented 16% of the HeartMate patients who underwent a CTA, or 8% of all HeartMate recipients within the timeframe analyzed. The resultant median values of minimal outflow luminal diameters within this subset were 13.5 mm (11−14 mm), with minimal areas of 160 $mm^2$ (152−183 $mm^2$).

Conversely, patients with HeartWares had variable amounts of biodebris surrounding the outflow graft, with the median largest aggregate diameter in any 1 cross-section of 2 mm (interquartile range 0−6 mm). Even with biodebris buildup as large as 12 mm in aggregate diameter, no patient had an internal luminal diameter of the outflow graft that was $< 10$ mm. Three patients had aggregate biodebris diameters $> 4$ mm, which prompted further measurements of minimum outflow graft luminal area; the range of areas was 110 to 125 $mm^2$, further demonstrating a lack of graft

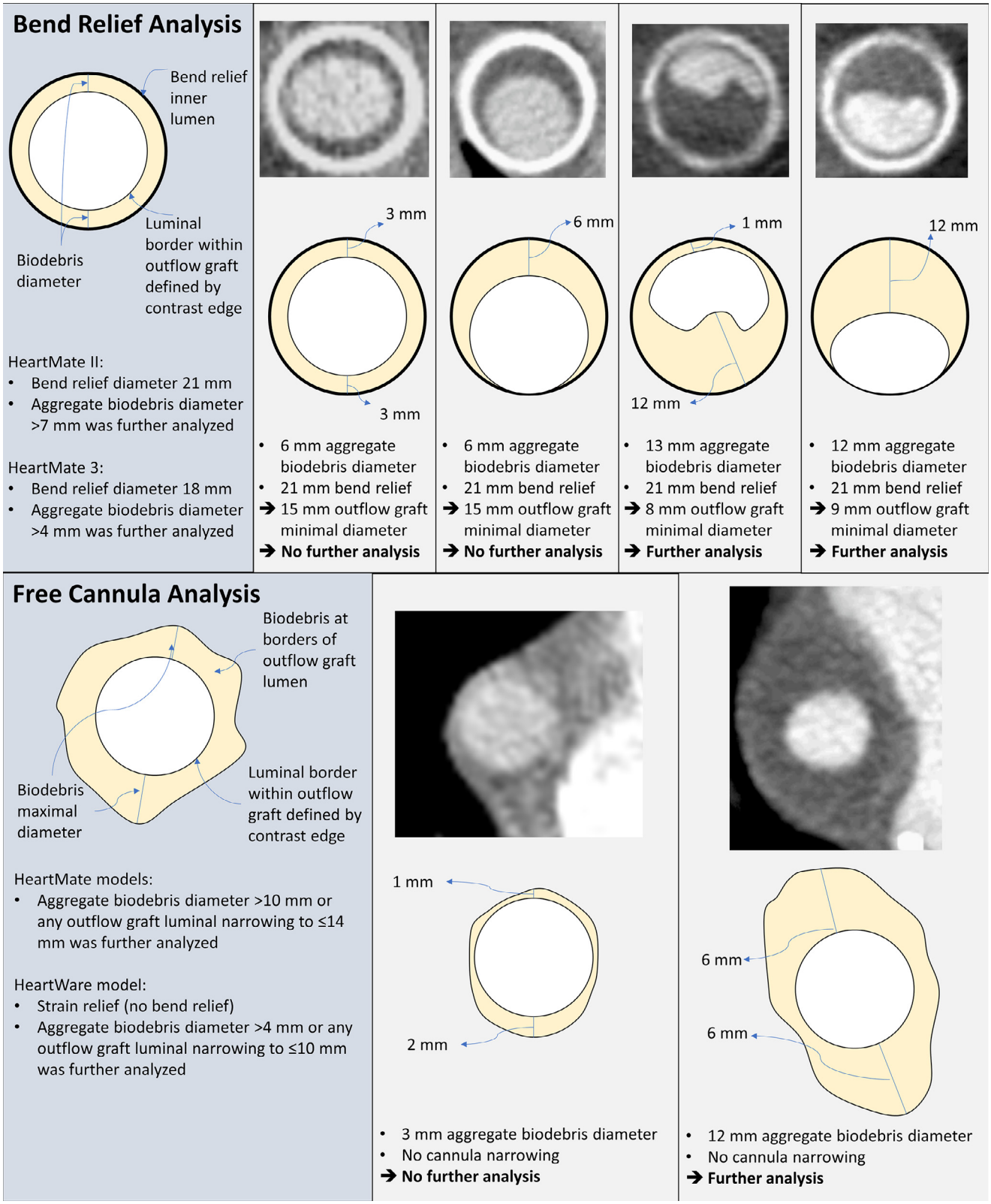


**Fig. 2.** Approach to imaging analysis.

narrowing. Biodebris accumulation measurements for both types of devices are demonstrated in Figure 3 (HeartMate II and 3 devices are shown separately due to the differences in device component dimensions).

In addition to these findings, 4 patients (all with HeartMate II devices) were found by CTA to have a kink in the outflow graft. One of these patients also had significant biodebris accumulation within the bend relief that resulted in luminal narrowing.

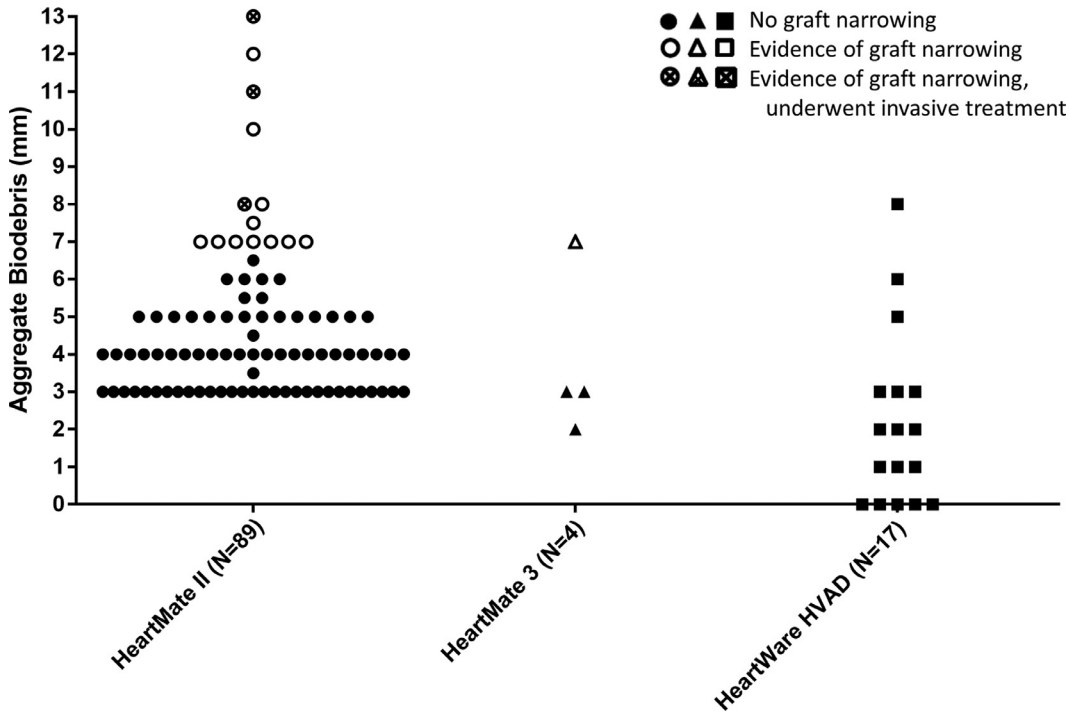


**Fig. 3.** Grouped scatter plot of the aggregate biodebris measurements based on device.

The characteristics of patients with outflow graft narrowing (not including kinking) compared to those who had CTAs without outflow graft narrowing are described in Table 2. Patients with outflow graft narrowing had CTAs longer after device implant, were more likely to have nonischemic cardiomyopathy and were more likely to have had the scan ordered to assess for pump thrombosis or impaired flow than those without evidence of narrowing. On multivariable analysis from exact logistic regression, time from implant to scan ($P < 0.001$), nonischemic

**Table 2.** Comparison of Patients With Computed Tomography Angiography Available to Analyze Based on Presence or Absence of Outflow Graft Narrowing

| | | Outflow graft narrowing (n = 15) | No outflow graft narrowing (n = 95) | *P* value |
|---|---|---|---|---|
| Time of device implant | Age at implant, years | 64 (46−71) | 55 (46−63) | 0.12 |
| | Gender, male | 8 (53%) | 71 (75%) | 0.12 |
| | Race, white | 9 (60%) | 44 (46%) | 0.41 |
| | Status, bridge to transplant | 4 (27%) | 41 (43%) | 0.27 |
| | Body mass index (kg/m2) | 29.5 (23.6−32.1) | 28.9 (24.9−34.0) | 0.64 |
| | Body surface area (m2) | 2.00 (1.90−2.18) | 2.17 (1.92−2.30) | 0.11 |
| | Ischemic cardiomyopathy | 1 (7%) | 33 (35%) | 0.03 |
| | Device | | | 0.12 |
| | HeartMate (HMII or HM3) | 15 (100%) | 78 (82%) | |
| | HeartWare HVAD | 0 (0%) | 17 (18%) | |
| | Left ventricular ejection fraction (%) | 15 (10−20) | 15 (10−20) | 0.78 |
| | Pump/perfusion time (minutes) | 88 (76−137) | 107 (78−145) | 0.34 |
| Time of CTA | Time from implant to scan (days) | 994 (242−1616) | 199 (55−462) | < 0.01 |
| | Reason for scan | | | |
| | Concern for pump thrombosis | 7 (47%) | 15 (16%) | 0.01 |
| | Infection | 4 (27%) | 48 (51%) | 0.10 |
| | Malignancy | 1 (7%) | 3 (3%) | 0.45 |
| | Trauma | 2 (13%) | 0 (0%) | 0.02 |
| | INR | 2.4 (2.0−3.1) | 2.1 (1.7−2.6) | 0.15 |
| | INR target | 2.5 (2.2−2.5) | 2.5 (2.5−2.7) | 0.45 |
| | Lactate dehydrogenase (units/L) | 348 (295-780) | 340 (263−509) | 0.39 |
| | Antiplatelet treatment | | | |
| | Aspirin | 6 (40%) | 35 (37%) | 1.00 |
| | P2Y12 inhibitor | 15 (100%) | 91 (96%) | 1.00 |
| | Dipyridamole | 14 (93%) | 89 (94%) | 1.00 |

CTA, computed tomography angiography; HM, HeartMate; INR, international normalized ratio.

**Table 3.** Exact Regression Analysis for Association With Outflow Graft Narrowing

| | Univariate model | | Multivariate model | |
|---|---|---|---|---|
| | Odds ratio (95% CI) | *P* value | Odds ratio (95% CI) | *P* value |
| Age at implant, years | 1.04 (0.99−1.09) | 0.093 | 1.09 (1.03−1.16) | 0.003 |
| Nonischemic Cardiomyopathy | 0.13 (0.02−1.07) | 0.044 | 13.0 (1.36−71.8) | 0.017 |
| Time from implant to scan (per 100 days) | 1.19 (1.09− 1.31) | <0.001 | 1.24 (1.12−1.41) | < 0.001 |

cardiomyopathy ($P = 0.017$) and age at device implant ($P = 0.003$) were significantly associated with LVAD outflow graft narrowing (Table 3). The AUC value was 0.869, indicating a successful separation based on the regression model between subjects with and without outflow graft narrowing. The 95% confidence interval for the AUC based on 2000 bootstrap samples was 0.764 to 0.977, demonstrating the utility of the 3 variables in a regression model framework for predicting the probability of outflow graft narrowing.

### Clinical Outcomes

Of the patients who had biodebris accumulation with luminal narrowing (all with HeartMate devices), 3 (20%) were referred for surgical or percutaneous intervention. One patient (minimum outflow graft diameter 10 mm, minimum cross-sectional area 132 $mm^2$) underwent surgical outflow cannula exchange, in which the surgeon discovered a large amount of fibrinous material between the bend relief and graft but no obvious intraluminal thrombus. Another patient (minimum outflow graft diameter 8 mm, minimum cross-sectional area 117 $mm^2$) underwent invasive graft examination with intravascular IVUS, revealing extrinsic compression of the graft from within the bend relief (rather than internal thrombus) and was treated with percutaneous stenting within the graft. The third patient with presumed thrombosis of the LVAD (minimum outflow graft diameter 13 mm, minimum cross-sectional area 173 $mm^2$) underwent complete device exchange, in which it was remarked that there was no evidence of thrombus within the pump, inflow cannula or outflow graft; the space between the bend relief and outflow graft was not commented on in the surgical report.

Four patients, all with HeartMate II devices, were found to have a kink in the outflow cannula. One patient was conservatively managed until transplant 21 months later; 1 patient underwent LVAD exchange 3 days after the CTA; 1 patient underwent percutaneous stenting of the kinked region to restore flow. Another patient with both kinking in the free portion of the cannula as well as biodebris buildup within the bend relief portion was managed conservatively and is still living on the device 17 months after the CTA at the time of this analysis.

In the group of patients who had CTAs to analyze, those with outflow graft narrowing not due to kinking (n = 15) were compared to those without narrowing (n = 95). At 30 days, there was a trend toward increased rates of the cumulative endpoint of death or outflow graft/LVAD intervention ($P = 0.06$), which was not sustained to 1 year ($P = 0.82$). There were no significant differences in the proportion of patients in either group who were clinically diagnosed with pump thrombosis (2 of 15 [13%] in the "outflow graft narrowing" group vs 9 of 95 [9%] in the "no outflow graft narrowing" group [$P = 0.64$]), nor were there significant differences in mortality rates after the scan to 1 year ($P = 0.96$).

## Discussion

LVADs have revolutionized advanced heart failure treatment but, as with any new technology, increased experience has revealed potential complications not identified in the initial trials. The purpose of our study was to evaluate the incidence and possible clinical significance of LVAD outflow graft compression.

In this retrospective analysis of 241 patients with LVADs implanted over an 8-year span at our institution, the key finding relating to outflow graft narrowing was that in the absence of outflow graft kinking (which was observed only in HeartMate II devices but was still rare in the CTA cohort), only patients with a bend relief structure that surrounded but was not in contact with the outer surface of the outflow graft (ie, patients with HeartMate devices) were found to have evidence of luminal narrowing. This narrowing was always within the portion of the graft covered by the bend relief structure. The finding affected a minority, but still sizable, portion of the patients with HeartMate devices (16% of HeartMate patients with CTAs to analyze), which is higher than that which has been described in other reports[4,5] and may be a result of our systematic analysis of scans in these patients, including in patients who had no clinical concerns about pump thrombosis. In the limited subset (n = 3) of patients who underwent invasive assessment of the outflow graft, there were no cases of intraluminal thrombus within the outflow graft. Rather, confirmatory assessments revealed buildup of biodebris within the bend relief structure, causing extrinsic compression, and we wonder whether this could be the predominant etiology in other cases.

This finding can have critical ramifications for patient care. When patients with LVADs show evidence of impaired flow or hemolysis, a CTA is commonly ordered early in the diagnostic workup.[7,8] Although it is a valuable tool, this modality is sometimes unable to define clearly the details of graft obstruction and is largely unable to interrogate the portion within the metallic pump. CTA can clearly define the innermost lumen of the outflow graft by examining the borders of the contrast agent, but when there is a narrowed portion, it is frequently unclear whether the luminal compromise originates from within the

outflow graft or is a result of extrinsic compression. Thus, the differential diagnosis includes etiologies with highly divergent treatment strategies.

Some published cases describe complete or near complete thrombosis of the outflow graft, which was managed conservatively[14] or surgically,[15–17] the latter allowing for confirmation of the diagnosis. This seems to be described commonly in the setting of concomitant stenosis at the site of outflow graft anastomosis to the aorta,[16,17] which perhaps predisposes the device to stasis of flow compared to normally functioning LVADs. The situation that occurs far more commonly than complete thrombosis, based on our analysis, is the finding of a small to moderate amount of buildup of biodebris along the outflow graft within the portion covered by the bend relief. Indeed, other cases in the literature feature images that resemble the cases we encountered, in which the patients were treated with stenting for presumed thrombus within the graft but without further confirmation of the diagnosis, and extrinsic compression from biodebris buildup within the bend relief was not excluded.[18–20]

Mehr et al provided a cautionary tale relating to cases like these by describing 2 patients with HeartMate II devices who were noted to have biodebris accumulation within the bend relief portion of the outflow graft, 1 of which was found at the time of surgery to have pump thrombosis but no internal thrombus of the outflow graft lumen.[21] They warned about the misleading appearance this phenomenon can have on CTA. Duero Posada et al similarly described this occurrence in 2 patients with HeartMate 3 devices in which biodebris accumulation between the graft and bend relief was found on surgical excision, reporting that they had not seen any outflow graft obstruction events in their other 13 patients with HeartMate 3.[22] In contrast to the clinical approach discussed in other publications, Bhamidipati et al reported 3 cases with similar findings on CTA that were assumed to represent extrinsic graft compression and, thus, were treated with noncovered stents, without mention of embolic protection.[23] Assuming that such impairment in outflow graft patency is due to extrinsic compression is more in line with our own clinical experience, in which patients with low flow events had CTAs initially suggestive of intraluminal thrombosis, but by IVUS were, in fact, demonstrated to be extrinsic compression resulting from buildup of biodebris within the bend relief.[9] This occurrence was treated by stenting within the graft, without the need for embolic protection, rather than by an intensified anticoagulation strategy or thrombolytics. We wonder whether some of the cases in the literature that indicate presumed outflow graft thrombus were actually cases of extrinsic compression.

To our knowledge, the current study is the first to review systematically a large sample of CTAs in patients with a spectrum of LVAD models, measure the biodebris accumulations (with or without clinical findings), and provide estimates of the prevalence, clinical associations and implications for clinical outcomes. It is notable that the majority of patients had outflow graft luminal diameters throughout the entire cannula that were greater than the preimplantation diameters (> 14 mm for the HeartMate devices and > 10 mm for the HeartWare), indicating radiographic evidence of expansion when exposed to the setting of LVAD flow and aortic blood pressure, thus establishing a "normal" appearance for these components radiologically.

The etiology of the biodebris external to the outflow graft remains somewhat elusive. Surgical experience from our center and similar case reports describe a material that is amorphous or an organized thrombus. On histologic analysis, this material is mostly fibrin debris within the bend relief.[22,23] The factors causing this biodebris to build progressively against a pressurized outflow graft are unclear. It has been speculated that the semiporous outflow graft allows for escape of the proteinaceous material and, for unclear reasons in a subset of patients, this material is trapped within the nonporous bend relief without the ability to reabsorb.[23] Patients with compression were significantly longer from their implant dates, and it is possible that this phenomenon would occur more commonly in patients who have had enough time to develop it. This point may explain to some extent the disproportionate representation of patients with HeartMate II who demonstrated this finding, because this device has been approved for destination therapy longer than the other 2 devices included in the analysis.

Although this study discovered presumed outflow graft compression only in HeartMate devices, our findings could be limited by the relatively small sample size of HeartWare patients. Indeed, HeartWare outflow graft compression has also been described.[24] Unlike the bend relief segments of HeartMate II and 3, which prevent fibrous growth into its material, the plastic rings covering the proximal outflow graft segment of HeartWare may scar and adhere to the surrounding tissue (right ventricle, diaphragm), posing a challenge at the time of heart transplantation or LVAD exchange. To mitigate this issue, at our institution surgeons wrap the strain relief segment with very thin GORE PRECLUDE membrane with interrupted sutures, which maintains tissue planes but allows fluid and debris to seep out without risking outflow graft compression. Indeed, recent reports have emerged that describe a similar form of compression if a closed tube is used to surround HVAD outflow cannulas.[25,26]

Frequently cited guidance documents that provide an algorithmic approach to diagnosing LVAD dysfunction describe incompletely the possibility of outflow graft extrinsic compression within the bend relief, and the role of diagnostic IVUS is not mentioned.[7,8] IVUS can be useful to demonstrate complete outflow graft thrombosis in the setting of aortic stenosis[16] or to prove that the outflow graft narrowing is not due to intramural thrombosis at all,[9,27] We recommend consideration of this modality in cases in which the diagnosis is unclear. In cases where there is extrinsic compression of the LVAD outflow graft, percutaneous treatment should be considered.

There are several limitations to this study, including retrospective analysis at a single center with a relatively small representation of HeartWare devices. Because of the retrospective nature of the study, we can only describe associations for hypothesis-generating purposes rather than draw definitive conclusions about causality. In addition, the number of cases

in which there was some form of invasive diagnostic confirmation was relatively small, and we did not perform an inter- or intraobserver variability assessment from our readers.

## Conclusion

In this retrospective review of patients with LVAD outflow grafts evaluated by CTA, we detected luminal narrowing in a minority, but still sizable, portion of patients with HeartMate devices, exclusively in the portion covered by the bend relief. Given the fact that biodebris appears to accumulate to some extent in all devices with this design, and based on the patients who underwent invasive assessment for their luminal narrowing, we speculate that, in many patients, these findings may be due to extrinsic compression of the graft rather than to intraluminal thrombus. Prospective studies are warranted to determine the clinical implications of LVAD outflow graft narrowing.

## Acknowledgments

We thank Le Kang, PhD, for his contribution to the statistical analysis.

## Statement of Authorship

Category 1

(a) Conception and Design
(b) Acquisition of Data
(c) Analysis and Interpretation of Data

Category 2

(a) Drafting the Article
(b) Revising It for Intellectual Content

Category 3

(a) Final Approval of the Completed Article

## References

1. Mozaffarian D, Benjamin EJ, Go AS, et al. Heart disease and stroke statistics, 2016 Update: A report from the American Heart Association, vol. 133; 2016.
2. Ponikowski P, Anker SD, AlHabib KF, et al. Heart failure: Preventing disease and death worldwide. ESC Heart Fail 2014;1:4–25.
3. Slaughter MS, Rogers JG, Milano CA, et al. Advanced heart failure treated with continuous-flow left ventricular assist device. N Engl J Med 2009;361:2241–51.
4. Mehra MR, Naka Y, Uriel N, et al. A fully magnetically levitated circulatory pump for advanced heart failure. N Engl J Med 2017;376:440–50.
5. Rogers JG, Pagani FD, Tatooles AJ, et al. Intrapericardial left ventricular assist device for advanced heart failure. N Engl J Med 2017;376:451–60.
6. US Department of Health and Human Services Food and Drug Administration. Abbott Implements Corrective Action for Heartmate 3 Heart Pump. Available at: https://www.fda.gov/safety/recalls/ucm609443.htm. Accessed 31 May 2018.
7. Goldstein DJ, John R, Salerno C, et al. Algorithm for the diagnosis and management of suspected pump thrombus. J Hear Lung Transplant 2013;32:667–70.
8. Scandroglio AM, Kaufmann F, Pieri M, et al. Diagnosis and treatment algorithm for blood flow obstructions in patients with left ventricular assist device. J Am Coll Cardiol 2016; 67:2758–68.
9. Trankle CR, Quader MA, Grizzard JD, et al. Internal versus external compression of a left ventricular assist device outflow graft: Diagnosis with intravascular ultrasound and treatment with stenting. Circ Hear Fail 2018;11:e004959.
10. Mellnick VM, Raptis DA, Raptis C, Bhalla S. Imaging of left ventricular device complications. J Thorac Imaging 2013;28:W35–41.
11. Thoratec Corporation. HeartMate II left ventricular assist system: Instructions for use; 2017.
12. Thoratec Corporation. HeartMate III left ventricular assist system: Instructions for use; 2018.
13. HeartWare. HeartWare HVAD system: Instructions for use; 2018.
14. Mishkin JD, Enriquez JR, Meyer DM, et al. Utilization of cardiac computed tomography angiography for the diagnosis of left ventricular assist device thrombosis. Circ Hear Fail 2012;5:27–9.
15. Raman SV, Sahu A, Merchant AZ, Louis IV LB, Firstenberg MS, Sun B. Noninvasive assessment of left ventricular assist devices with cardiovascular computed tomography and impact on management. J Hear Lung Transplant 2010;29:79–85.
16. Smith ES, Nelson MT, Tang DG. Intraoperative use of vascular ultrasound to localize thrombus in left ventricular assist device exchange. Anesth Analg 2016;122:27–9.
17. Tran BC, Nijjar PS. Role of contrast CT for the diagnosis and the prognosis of suspected LVAD thrombosis. J Card Surg 2017;32:162–5.
18. Abraham J, Remick JD, Caulfield T, et al. Left ventricular assist device outflow cannula obstruction treated with percutaneous endovascular stenting. Circ Hear Fail 2015;8:229–30.
19. Retzer EM, Tannenbaum SA, Fedson SE, et al. Successful percutaneous trans-catheter treatment of left ventricular assist device outflow graft stenosis with a covered stent. ESC Hear Fail 2015;2:100–2.
20. Hubbert L, Forssell C, Baranowski J, Lindgren B, Holm J, Ahn H. Endovascular stenting of a LVAD outflow graft thrombosis. ASAIO J 2017;63:e3–5.
21. Mehr AJ, Kwan MD, Kunavarapu C. Thrombus detected in computed tomography angiography images of HeartMate II outflow graft: A cautionary tale. J Hear Lung Transplant 2014;33:1193–4.
22. Duero Posada JG, Moayedi Y, Alhussein M, et al. Outflow graft occlusion of the HeartMate 3 left ventricular assist device. Circ Hear Fail 2017;10:e004275.
23. Bhamidipati CM, Pal JD, Jones TK, et al. Outflow graft obstruction treated with transcatheter management: A novel therapy for a new diagnosis. Ann Thorac Surg 2017;103:e101–4.
24. Young RK, Majure DT, Sheikh FH, et al. Outflow graft obstruction of the Heart Ware HVAD left ventricular assist device: A single-center case series. J Hear Lung Transplant 2016;35:S265.
25. Potapov E, Kaufmann F, Mueller M, Mulzer J, Starck C, Falk V. Avoidance of outflow graft extrinsic compression in polytetrafluoroethylene reinforcements of the bend relief component. J Hear Lung Transplant 2019. [Epub ahead of print].
26. Alnabelsi T, Shafii AE, Gurley JC, Dulnuan K, Harris DD, Guglin M. Left ventricular assist device outflow graft obstruction: A complication specific to polytetrafluoroethylene covering: A word of caution! ASAIO J 2018. [Epub ahead of print].
27. Moran HRM, Kass M, Ravandi A, Zieroth S, Arora RC, Singal RK. Diagnosis of left ventricular assist device outflow graft obstruction using intravascular ultrasound. Circ Hear Fail 2016;9:e003472.