

# Preoperative Pectoralis Muscle Quantity and Attenuation by Computed Tomography Are Novel and Powerful Predictors of Mortality After Left Ventricular Assist Device Implantation

**BACKGROUND:** Skeletal muscle mass decreases in end-stage heart failure and is predictive of clinical outcomes in several disease states. Skeletal muscle attenuation and quantity as quantified on preoperative chest computed tomographic scans may be predictive of mortality after continuous flow (CF) left ventricular assist device (LVAD) implantation.

**METHODS AND RESULTS:** A single-center continuous flow-LVAD database (n=354) was used to identify patients with chest computed tomographies performed in the 3 months before LVAD implantation (n=143). Among patients with computed tomography data available, unilateral pectoralis muscle mass indexed to body surface area and attenuation (approximated by mean Hounsfield units [PHU<sub>m</sub>]) were measured in each patient with a high intrarater and inter-rater reliability (intraclass correlation coefficients 0.98 and 0.97, respectively). Multivariate Cox regression analyses were performed, censoring at cardiac transplantation, to assess the impact of preoperative pectoralis muscle index and pectoralis muscle mean Hounsfield unit on survival after LVAD implantation. Each unit increase in pectoralis muscle index was associated with a 27% reduction in the hazard of death after LVAD (adjusted hazard ratio, 0.73; 95% confidence interval, 0.58–0.92; *P*=0.007). Each 5-U increase in pectoralis muscle mean Hounsfield unit was associated with a 22% reduction in the hazard of death after LVAD (adjusted hazard ratio, 0.78; 95% confidence interval, 0.68–0.89; *P*<0.0001). Pectoralis muscle index and pectoralis muscle mean Hounsfield unit outperformed other traditional measures in the data set, including the HeartMate II risk score.

**CONCLUSIONS:** Pectoralis muscle size and attenuation were powerful predictors of outcomes after LVAD implantation in this data set. This one time, repeatable, internal assessment of patient substrate added valuable prognostic information that was not available on standard preoperative testing.

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### WHAT IS NEW?

- Advanced heart failure is a systemic disorder and associated with sarcopenia and frailty, which may not be responsive to therapies such as left ventricular assist device (LVAD) support.
- Chest computed tomography scans are often obtained as a standard of care prior to LVAD implantation and can be used to routinely assess skeletal muscle that is part of the image.
- In this study, the pectoralis muscle's attenuation and quantity as quantified on pre-operative chest computed tomography scans are predictive of mortality after continuous flow left ventricular assist device (CF-LVAD) implantation.

### WHAT ARE THE CLINICAL IMPLICATIONS?

- Pectoralis muscle attenuation and size is a one time, objective measure that added valuable prognostic information to standard pre-operative testing.
- This measure has the potential to improve clinical decision making in this population.
- Whether or not sarcopenia improves with LVAD therapy awaits further study.

Left ventricular assist device (LVAD) implantation extends the survival of patients with end-stage systolic heart failure compared with medical therapy.<sup>1</sup> More than 15 000 LVADs have been implanted in the United States to date, and the number per year is increasing rapidly.<sup>2</sup> Although technological advances and experience in this field have led to improved survival over time,<sup>3</sup> there is a subset of patients with high mortality and hospitalization rates after LVAD implantation, even in clinical trial settings.<sup>1,4</sup> As the number of heart failure cases continues to rise, it is increasingly important to accurately predict which candidates will have a favorable course on LVAD support.

Skeletal muscle mass decreases in end-stage heart failure before overt weight loss and is increasingly recognized as a biomarker of outcomes in several disease states.<sup>5,6</sup> It was recently demonstrated that preoperative psoas muscle mass indexed to body surface area, quantified on preoperative computed tomographic (CT) scans, was associated with increased length of stay in the LVAD population<sup>7</sup>; however, there was not a mortality difference in this study, and muscle attenuation was not assessed. Because CT scans of the chest are often performed as part of LVAD surgical planning, we analyzed the pectoralis muscle as a potential predictor of outcomes based on previous studies in nonheart failure populations.<sup>8–10</sup> In this study, we report that unilateral pectoralis muscle attenuation<sup>11</sup> and quantity indexed to height (PHU<sub>m</sub> and PMI, respectively) were powerful predictors of mortality after LVAD and outperformed other traditional clinical variables tested in this data set.

## METHODS

### Cohort

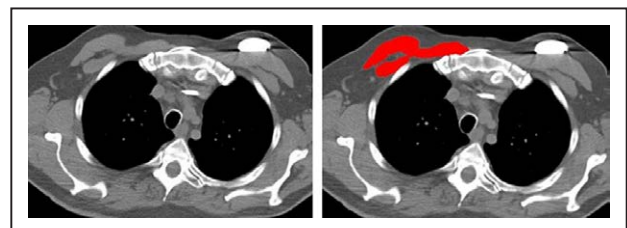
The institutional review board of the University of Minnesota approved this study. A waiver of consent was obtained due to the nature of the study. The larger cohort included patients who underwent continuous flow-LVAD implantation at the University of Minnesota from January 1, 2005, to July 1, 2016 (n=354). Patients with chest CTs performed within the 3 months before LVAD implantation were included in the analysis (n=143).

### CT Analysis

Methods of pectoralis muscle analysis were based on the work conducted by Kinsey et al.<sup>9</sup> Measures of cross-sectional area in cm<sup>2</sup> and mean Hounsfield units were obtained using Slice-O-Matic V5.0 software (Tomovision, Montreal, Canada) by a single reader who was blinded to patient outcomes. Once images were obtained in DICOM format, 5 to 10 minutes were required to measure each scan. Unilateral pectoralis muscle measurements were performed on a single axial slice directly superior to the aortic arch on the patient's right side. If a defibrillator was present on the right, the left pectoralis muscle was analyzed instead (n=7). Muscles were manually shaded using a predefined attenuation range of -29 to 150 (Figure 1) to obtain the mean Hounsfield Units (PHU<sub>m</sub>) and cross-sectional area (cm<sup>2</sup>). Cross-sectional area measures were standardized for body size by dividing by height in square meters (m<sup>2</sup>); this produced the measure of pectoralis muscle index (PMI; cm<sup>2</sup>/m<sup>2</sup>). To determine intrarater variability, a random subsample of scans (n=30) were analyzed a second time at least 2 weeks after completing initial measurements. To determine inter-rater variability, the same subsample of scans (n=30) were analyzed by a practicing cardiologist. Reliability was assessed with intraclass correlation coefficients.<sup>12,13</sup> Intra-class correlation coefficient values were generated using SAS Version 9.4 (SAS Institute, Cary, NC).

### Outcome and Covariates

The outcome of interest was time to all-cause mortality. Vital status was obtained from chart review and was current through July of 2016. The date of the last clinic visit was



**Figure 1.** Axial computed tomographic (CT) image demonstrating measurement of unilateral pectoralis muscle.

Axial CT images of the pectoralis major and minor at a level directly above the aortic arch. The image on the **left** is the original scan. The image on the **right** has been manually shaded using a Hounsfield unit range of -29 to 150. The program used to analyze the image produced measures of cross-sectional area in cm<sup>2</sup> and mean Hounsfield units of the shaded area.

recorded for patients who were still alive at the end of follow-up. For cardiac transplantation, the date of cardiac transplant was obtained from the electronic medical record and confirmed with an operative report.

The following demographic and clinical covariate data are available in the University of Minnesota LVAD database, which is updated yearly through data extraction and manual chart review: age, sex, body mass index (BMI), creatinine, albumin, prealbumin, NT-proBNP (N-terminal pro-B-type natriuretic peptide), international normalized ratio, Interagency Registry for Mechanical Circulatory Support (INTERMACS) profile, preoperative hemodynamics, bridge to transplant status, cardiomyopathy type, and presence or absence of diabetes mellitus. HeartMate II Risk Scores were calculated on each patient in the following way: HMII Risk Score=(0.0274×[age in years])+(0.723×[albumin g/dL])+(0.74×[creatinine mg/dL])+(1.136×[international normalized ratio])+(0.807×center volume<15).<sup>14</sup> As our center implants >15 LVADs per year, the last term of the score was zero for all patients.

## Statistical Analysis

All statistics were performed with STATA version 14 (StataCorp, College Station, TX). Histograms were created for the pectoralis muscle measures to assess for normality of distribution. Baseline characteristics of patients with and without chest CTs were compared with *t* tests for normally distributed variables and Wilcoxon rank-sum tests for non-normally distributed continuous variables. Tertiles were then created for both pectoralis muscle measures (PMI and PHU<sub>m</sub>). Baseline characteristics across tertiles of pectoralis measures were compared using 1-way ANOVA for normally distributed and Kruskal–Wallis tests for non-normally distributed continuous variables. All categorical variables were compared with Pearson  $\chi^2$  tests. To assess the relationship between pectoralis muscle attenuation (PHU<sub>m</sub>) and quantity (PMI), a scatterplot was created and the association was tested with a Pearson correlation analysis. One-way ANOVA was used to compare the mean PMI and PHU<sub>m</sub> across INTERMACS profiles.

To assess the impact of preoperative PMI and PHU<sub>m</sub> on mortality, Kaplan–Meier survival analyses were performed. The survival between tertiles was compared using the log-rank test. Multivariable Cox regression analyses were then performed to assess the adjusted impact of preoperative pectoralis muscle measures on mortality after LVAD. As cardiac transplantation represents a competing risk in this analysis, patients were censored at the time of transplantation in the primary analysis. To ensure the robustness, the measured associations and to account for this competing risk using a different methodology, the analysis was repeated using the Fine Gray method.<sup>15,16</sup> Prespecified potential confounders of the relationship between pectoralis muscle measures and post-LVAD mortality including sex, HeartMate II risk score, total bilirubin, year of implant, BMI, INTERMACS profile, prealbumin, right atrial pressure, bridge to transplant status, and log (NT-proBNP) were then added to the models and tested for significance in a univariate exploratory analysis ( $P<0.2$ ). These were then incorporated in a forward and backward stepwise fashion using the likelihood ratio test for significance to arrive at a final adjusted model. Preoperative PMI and PHU<sub>m</sub> were then assessed in a combined model. To determine whether the relationship between pectoralis muscle measures and mortality was linear, quadratic terms for PMI and PHU<sub>m</sub> were generated and tested in the Cox regression models.

The following variables were then tested individually in this data set to assess for association with mortality using Fine Gray Cox regression: sex, HeartMate II risk score, total bilirubin, year of implant, BMI, INTERMACS profile, prealbumin, right atrial pressure, and log (NT-proBNP).

For all analyses, a probability value of <0.05 was considered significant.

## RESULTS

### Cohort

Demographic and clinical characteristics of the cohort with and without chest CT scans available are presented in Table 1. Patients with CT scans available for analysis were older (60 versus 56 years;  $P=0.01$ ), more likely to be male (89% versus 74%;  $P=0.001$ ), more likely to have ischemic cardiomyopathy (62% versus 49%;  $P=0.017$ ) and to be diabetic (34% versus 19%;  $P=0.001$ ) than the larger cohort. The median follow-up time for the 143 patients included in the analysis was 538 days. During this time, 23 patients (16%) underwent cardiac transplantation.

### Pectoralis Muscle Measures

Intrarater variability was found to be 0.99 (intraclass correlation coefficient). Inter-rater variability was found to be 0.97 (intraclass correlation coefficient). PMI and

**Table 1. Clinical and Demographic Characteristics of Patient Cohort, by the Presence or Absence of Preoperative Chest CTs**

	With Chest CT, n=143	Without Chest CT, n=210	P Value
Age, y	60±13	56±13	0.008
Male	127 (89)	155 (74)	0.001
White	110 (77)	152 (72)	0.99
Ischemic cardiomyopathy	89 (62)	102 (49)	0.02
Bridge to transplant	80 (56)	137 (65)	0.06
INTERMACS profile			0.42
1	12 (8)	23 (11)	
2–3	54 (38)	70 (33)	
4–7	77 (54)	115 (55)	
Creatinine, mg/dL	1.2 [1.0–1.7]	1.2 [1.0–1.6]	0.49
Diabetes mellitus	49 (34)	39 (19)	0.001
BMI, kg/m <sup>2</sup>	29±6	29±6	0.75
Albumin, g/dL	3.4±0.6	3.5±0.6	0.17
Prealbumin, mg/dL	18±7	17±7	0.28
NT-proBNP, pg/mL	6075 [3096–12 125]	5130 [2500–10 200]	0.36
Chronic obstructive pulmonary disease	21 (15)	13 (6)	0.009

Values are presented as mean±SD, frequency (%), and median [IQR].

BMI indicates body mass index; CT, computed tomography; INTERMACS, Interagency Registry for Mechanical Circulatory Support; IQR, interquartile range; and NT-proBNP, N-terminal pro-B-type natriuretic peptide.

**Table 2. Unilateral Pectoralis Muscle Index (PMI; cm<sup>2</sup>/m<sup>2</sup>) Tertile Comparison**

	Lowest Tertile	Middle Tertile	Highest Tertile	P Value
	n=48	n=48	n=47	
PMI, cm <sup>2</sup> /m <sup>2</sup>	3.5±0.9	5.3±0.5	7.9±1.3	
Age, y	63±11	62±12	56±14	0.02
Male	41 (85)	44 (92)	42 (89)	0.62
Ischemic diagnosis	34 (71)	24 (50)	31 (66)	0.09
INTERMACS				
1	5 (10)	3 (6)	4 (9)	0.526
2–3	22 (46)	17 (35)	15 (32)	
4–7	21 (44)	28 (58)	28 (60)	
Diabetes mellitus	15 (31)	17 (35)	17 (36)	0.86
BMI, kg/m <sup>2</sup>	26±5	29±5	31±5	<0.0001
Creatinine, mg/dL	1.1 [0.9–1.6]	1.4 [1.0–2.0]	1.3 [1.1–1.6]	0.03
Albumin, g/dL	3.2±0.6	3.5±0.4	3.6±0.6	<0.01
Prealbumin, mg/dL	16±6	20±7	21±5	<0.01
NT-proBNP, pg/mL	9940 [5240–16 353]	6260 [3640–13 100]	3590 [1570–6780]	<0.0001

Values are presented as mean±SD, frequency (%), and median [IQR]. BMI indicates body mass index; INTERMACS, Interagency Registry for Mechanical Circulatory Support; IQR, interquartile range; and NT-proBNP, N-terminal pro-B-type natriuretic peptide.

PHU<sub>m</sub> measures were approximately normally distributed (Figures I and II in the [Data Supplement](#)). Pectoralis muscle measurements (PMI and PHU<sub>m</sub>) were correlated with one another ( $R=0.47$ ;  $P<0.0001$ ). This relationship is pictorially displayed in Figure III in the [Data Supplement](#). Mean PMI and PHU<sub>m</sub> by INTERMACS profile is displayed in Figure IVA and IVB in the [Data Supplement](#). Mean PMI and PHU<sub>m</sub> both decreased as disease severity increased ( $P<0.05$ , both PMI and PHU<sub>m</sub>).

### Baseline Characteristics by Pectoralis Muscle Measure Tertiles

Baseline characteristics by PMI and PHU<sub>m</sub> tertiles are presented in Tables 2 and 3, respectively. For PMI, patients in the lower tertiles were older and had lower BMIs, albumin, and prealbumin compared with those in higher tertiles. Furthermore, individuals in the lower tertiles of PMI measures had higher NT-proBNP. There was no

**Table 3. Unilateral Pectoralis Muscle Mean Hounsfield Unit (PHU<sub>m</sub>) Tertile Comparison**

	Lowest Tertile	Middle Tertile	Highest Tertile	P Value
	n=48	n=48	n=47	
PMUm	15±10	30±2	40±6	
Age, y	59±11	60±14	62±13	0.54
Male	43 (90)	40 (83)	44 (94)	0.28
Ischemic diagnosis	32 (67)	31 (65)	26 (55)	0.48
INTERMACS				
1	6 (13)	2 (4)	4 (9)	0.58
2–3	17 (35)	21 (44)	16 (34)	
4–7	25 (52)	25 (52)	27 (57)	
Diabetes mellitus	20 (42)	17 (35)	12 (26)	0.25
BMI, kg/m <sup>2</sup>	29±6	29±5	28±5	0.34
Creatinine, mg/dL	1.2 [1.0–1.8]	1.2 [0.9–1.5]	1.3 [1.0–1.8]	0.21
Albumin, g/dL	3.2±0.5	3.4±0.6	3.5±0.5	0.10
Prealbumin, mg/dL	15±6	19±6	21±6	<0.01
NT-proBNP, pg/mL	7663 [3090–12 000]	6598 [3460–15 256]	4220 [2160–10 200]	0.24

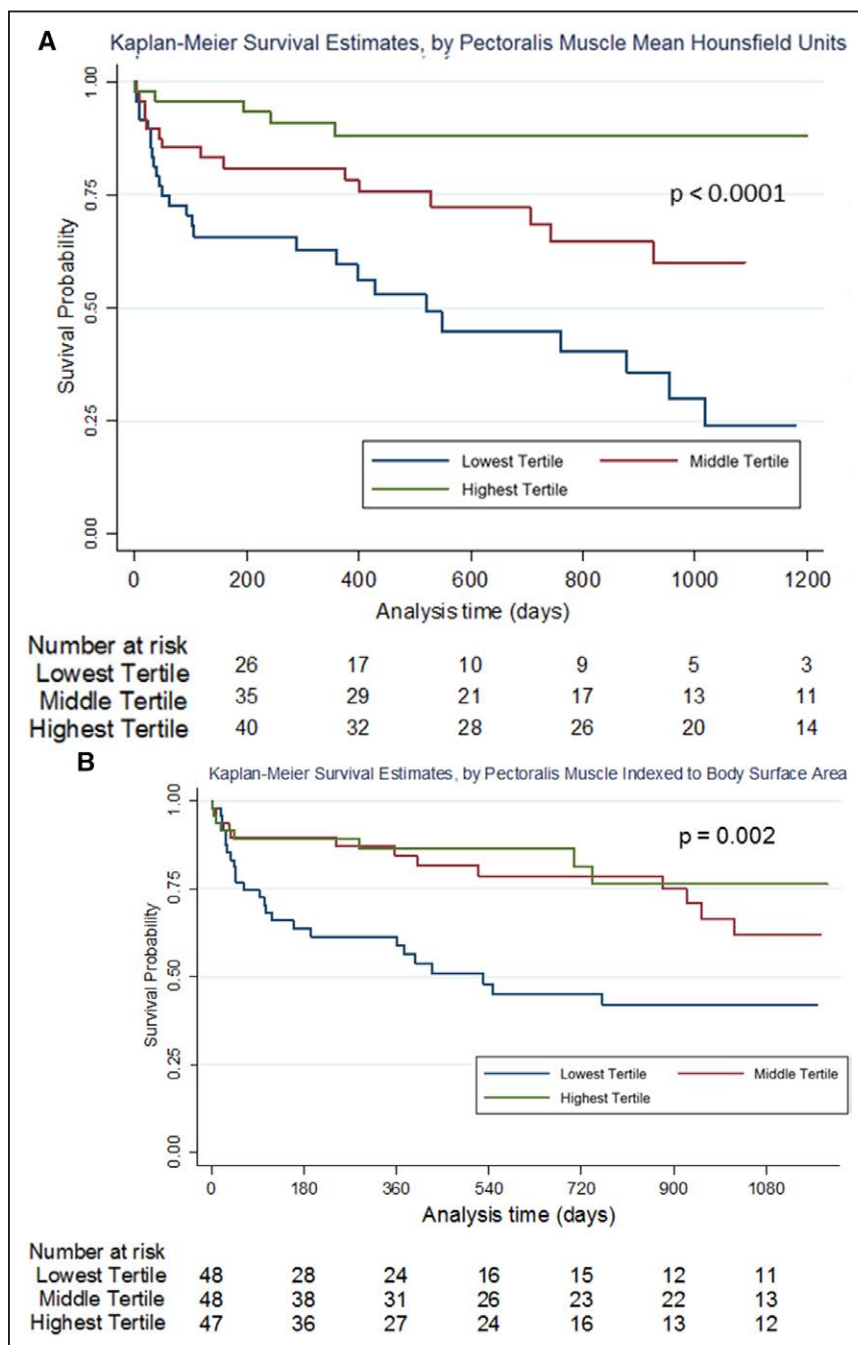
Values are presented as mean±SD, frequency (percent), and median [IQR]. BMI indicates body mass index; INTERMACS, Interagency Registry for Mechanical Circulatory Support; IQR, interquartile range; and NT-proBNP, N-terminal pro-B-type natriuretic peptide.

association between age, BMI or NT-proBNP, and PHU<sub>m</sub>. Prealbumin was significantly decreased in the lower tertiles compared with the higher tertiles of PHU<sub>m</sub>.

### Pectoralis Muscle Measures Were Highly Associated With Survival After LVAD

Kaplan–Meier estimates were generated by PHU<sub>m</sub> and PMI tertiles (Figure 2A and 2B). The estimated 1-year survival for patients after LVAD by PHU<sub>m</sub> tertile was the following: highest 88%, middle 81%, and lowest 59% ( $P < 0.0001$  by log-rank test). For PMI, the estimated sur-

vival by tertile was the following: highest 86%, middle 84%, and lowest 59% ( $P = 0.002$  by log-rank test). Hazard ratios (HRs) for LVAD mortality based on measures of unilateral pectoralis muscle are shown in Table 4. Each unit increase in PMI was associated with a 27% reduction in the hazard of death after LVAD (adjusted HR, 0.73; 95% confidence interval [CI], 0.58–0.92;  $P = 0.007$ ). Each 5-U increase in PHU<sub>m</sub> was associated with a 22% reduction in the hazard of death after LVAD (adjusted HR, 0.78; 95% CI, 0.68–0.89;  $P < 0.0001$ ). In the Fine Gray competing risk analysis, each 5-U increase in PHU<sub>m</sub> was associated with a 24% reduction in the



**Figure 2.** Kaplan–Meier survival estimates for unilateral pectoralis muscle measurements.

**A**, Kaplan–Meier survival estimates by pectoralis muscle mean Hounsfield unit (PHU<sub>m</sub>) tertiles ( $P < 0.0001$  by log-rank test). **B**, Kaplan–Meier survival estimates by pectoralis muscle indexed to height (PMI; cm<sup>2</sup>/m<sup>2</sup>) tertiles ( $P = 0.002$  by log-rank test).



**Table 4. Hazard Ratios for LVAD Mortality Based on Measures of Unilateral Pectoralis Muscle**

All-Cause Mortality, Transplants Censored							
Pectoralis Muscle, Mean Hounsfield Units				Pectoralis Muscle Indexed to Height, cm <sup>2</sup> /m <sup>2</sup>			
Model 1*	0.78	0.71–0.86	<0.0001	Model 1	0.77	0.65–0.89	0.001
Model 2†	0.78	0.71–0.86	<0.0001	Model 2	0.75	0.64–0.88	<0.0001
Model 3‡	0.78	0.68–0.89	<0.0001	Model 3	0.73	0.58–0.92	0.007

LVAD indicates left ventricular assist device; and NT-proBNP, N-terminal pro-B-type natriuretic peptide.

\*Model 1: unadjusted.

†Model 2: model 1+age, sex.

‡Model 3: sex, Heart Mate II risk score, diabetes mellitus, implant year, body mass index, Interagency Registry for Mechanical Circulatory Support profile, log NT-proBNP, right atrial pressure, and bridge to transplant status.

hazard of death after LVAD (HR, 0.76; 95% CI, 0.67–0.86;  $P<0.0001$ ). For PMI, each unit increase in PMI was associated with a 31% reduction in the hazard of death after LVAD (HR, 0.69; 95% CI, 0.55–0.87;  $P=0.002$ ). When PMI and PHU<sub>m</sub> were added to the models simultaneously, both measures remained significant (PMI: HR, 0.80; 95% CI, 0.66–0.98;  $P=0.03$  and PHU<sub>m</sub>: HR, 0.85 per 5 U increase in PMI; 95% CI, 0.75–0.96;  $P=0.01$ ). The quadratic terms for PMI and PHU<sub>m</sub> were not significant when tested in the models (PMI quadratic  $P=0.83$ , PHU<sub>m</sub> quadratic  $P=0.16$ ).

### PMI and PHU Compared With Other Covariates

In our data set, prealbumin, INTERMACS profile, BMI, and right atrial pressure were not predictive of mortality both in univariate and multivariate models (Table 5). The HeartMate II risk score was predictive in the univariate model (HR, 1.26; 95% CI, 1.00–1.5;  $P=0.03$ ), but not the multivariate models (HR, 1.26; 95% CI, 0.96–1.6;  $P=0.09$ ). Total bilirubin was also predictive in the univariate, but not the multivariate models (univariate HR, 1.24; 95% CI, 1.04–1.5;  $P=0.02$  and multivariate HR, 1.06; 95% CI, 0.8–1.4;  $P=0.70$ ).

## DISCUSSION

Our findings indicate that PMI and PHU<sub>m</sub> were strong prognostic markers for mortality after LVAD implantation. These markers outperformed other traditional clinical variables in terms of strength of association and statistical significance in this data set. Although these measures correlated with one another, they still remained significant individually in the combined models suggesting that tissue quantity and attenuation are both important in risk assessment. Pectoralis muscle attenuation was not associated with age or BMI, suggesting that this variable may reveal something novel about the patient's health that is not apparent on routine preoperative testing.

It has been demonstrated previously that patients can have low skeletal muscle and be obese, which may explain why these measures outperformed BMI in our data set.<sup>17</sup> It is also well described that while albumin and prealbumin correlate with nutritional state in healthy individuals, their nature as acute-phase reactants limits interpretation in the clinical setting. Our findings complement previous work by Heberton et al,<sup>7</sup> which demonstrated the prognostic ability of psoas muscle area determined by CT. The combination of these findings supports the

**Table 5. Association of Common Clinical Variables With Mortality in the Larger Cohort of LVAD Patients With Pectoralis Muscle Measures**

	Univariate HR	95% CI	P Value	Adjusted HR	95% CI	P Value
Age	1.00	0.98–1.02	0.80	0.99	0.96–1.02	0.59
HeartMate II Risk Score	1.26	1.00–1.5	0.03	1.26	0.96–1.6	0.09
INTERMACS profile	0.89	0.75–1.07	0.21	0.85	0.70–1.04	0.11
BMI, kg/m <sup>2</sup>	1.03	0.98–1.09	0.26	1.03	0.94–1.13	0.50
Total bilirubin, mg/dL	1.24	1.04–1.5	0.02	1.06	0.80–1.4	0.70
Prealbumin, mg/dL	0.94	0.87–1.02	0.15	1.03	0.90–1.2	0.71
Right atrial pressure, mmHg	1.04	0.99–1.08	0.08	1.01	0.96–1.10	0.84
NT-proBNP, pg/mL	1.09	0.85–1.40	0.52	0.81	0.62–1.06	0.12

All models adjusted for the above covariates minus the predictor variable including HeartMate II risk score, sex, INTERMACS profile, BMI, total bilirubin, prealbumin, right atrial pressure, bridge to transplant, diabetes mellitus, log of NT-proBNP, and implant year.

For age, the HeartMate II risk score was taken out of the model and INR and albumin were added.

BMI indicates body mass index; CI, confidence interval; HR, hazard ratio; INR, international normalized ratio; INTERMACS, Interagency Registry for Mechanical Circulatory Support; LVAD, left ventricular assist device; and NT-proBNP, N-terminal pro-B-type natriuretic peptide.

use of available technologies for skeletal muscle assessment in order to provide novel prognostic information not accounted for in conventional risk models.

Although several more clearly defined terms exist, the muscle wasting and loss of strength that accompany heart failure<sup>5,18–20</sup> are often broadly referred to as frailty.<sup>21,22</sup> Although frailty lacks a consensus definition, it has been shown to be an important prognostic marker in LVAD therapy.<sup>22–24</sup> It is not surprising that low muscle mass, which correlates with frailty, was strongly associated with mortality in this data set. These CT obtained measures, however, have the advantage of being highly repeatable and easily obtained in patients who may not be well enough to perform traditional frailty assessments.

There are 2 considerable differences between this study and the study of Heberton et al<sup>7</sup>: anatomic location of the measurement and inclusion of the muscle attenuation measure. It is possible that a muscle, such as the pectoralis muscle, is more reflective for the development of frailty compared with spinal muscles because of the maintenance of upright posture until later in illness, but this requires further exploration. Furthermore, the abdominal region is more prone to edema, which may influence the discrimination of the various parameters, particularly muscle attenuation.<sup>25</sup> Finally, to our knowledge, this is the first report of muscle attenuation by CT scan demonstrating strong predictive ability in the LVAD population. The physiological significance of muscle attenuation is incompletely understood, but it is often interpreted as a surrogate marker for tissue quality and has been demonstrated to be of prognostic value in several clinical conditions.<sup>11,25</sup>

Incorporation of pectoralis muscle measures may allow the development of more accurate prediction models not only to predict mortality after LVAD but also to predict repeated hospitalization. This type of tool would be helpful for patient and provider decision making around the time of LVAD implantation. Given the stepwise decrease in these measures by INTERMACS profile, it may be that these skeletal muscle measures will allow for a more accurate categorization of patients with end-stage disease. If these measures are incorporated into testing along with cardiopulmonary stress testing and right heart catheterization, we may be able to enhance clinical decision making and, ultimately, make strides toward identifying ideal implantation timing, which is presently unknown.<sup>26</sup>

## Limitations

This was a retrospective, small study. Despite this, there was a strong signal of accurate mortality prediction that held up in all statistical models. Important variables, such as quality of life and frailty assessment, are not included in this study. We do not have data on quality-of-life outcomes on enough patients to know whether

there is an association with quality of life after LVAD and preoperative skeletal muscle measures. We do not have common frailty measures in this data set to know whether these measures correlate with patient frailty<sup>22</sup>; however, patients are often too ill to perform traditional frailty assessments at the time of consideration of LVAD implantation, and chest CTs can always be performed. The patients who had chest CTs available for analysis were older and had more comorbidities than the larger LVAD population at our center. It will be important to validate these findings in a prospective data set where CT scans are performed in all subjects. The data included a small number of women, and although this was adjusted for in the multivariate analyses, this will need to be assessed in a larger group of female LVAD recipients to determine whether these findings are applicable to both male and female populations with heart failure. Finally, it is important to acknowledge the susceptibility of any CT measures of quantity and attenuation to changes in x-ray techniques. The measures of quantity and attenuation in this cohort were found to be powerful predictors of outcomes after LVAD when used as a general characterization of clinical status, but caution should be taken with the use of any absolute value to dichotomize individuals to above and below a specific cut point (ie, absolute cut-offs cannot be derived from this study).

## Conclusions

Pectoralis muscle size and attenuation were powerful predictors of outcomes after LVAD implantation in this data set. This one time, repeatable, internal assessment of patient substrate added valuable prognostic information that was not available on standard preoperative testing. Multicentered studies in larger and more diverse populations are needed to confirm these findings.

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## DISCLOSURES

Dr John is a member of the Abbott Speaker's Bureau and received Abbott research grants. Dr Cogswell is a member of the Abbott Speaker's Bureau, and her husband received stock options from Medtronic because of the nature of his employment. The other authors report no conflicts.

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## FOOTNOTES

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*Circ Heart Fail* is available at <http://circheartfailure.ahajournals.org>.

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### Preoperative Pectoralis Muscle Quantity and Attenuation by Computed Tomography Are Novel and Powerful Predictors of Mortality After Left Ventricular Assist Device Implantation

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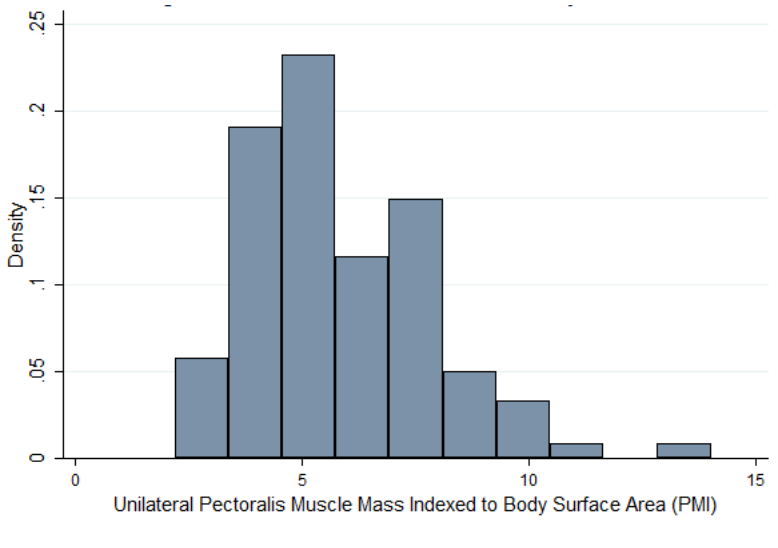
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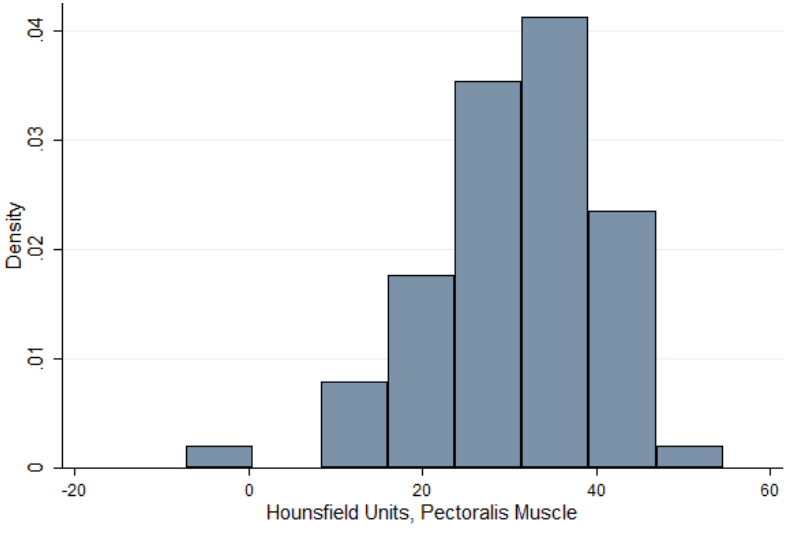
## **SUPPLEMENTAL MATERIAL**

**Supplementary Figure 1 – Distribution of Pectoralis Muscle Index Measures**



Distribution of unilateral pectoralis muscle index (PMI). This variable was generated by indexing cross-sectional area ( $\text{cm}^2$ ) of unilateral pectoralis muscle measures to height in meters squared ( $\text{cm}^2/\text{m}^2$ )

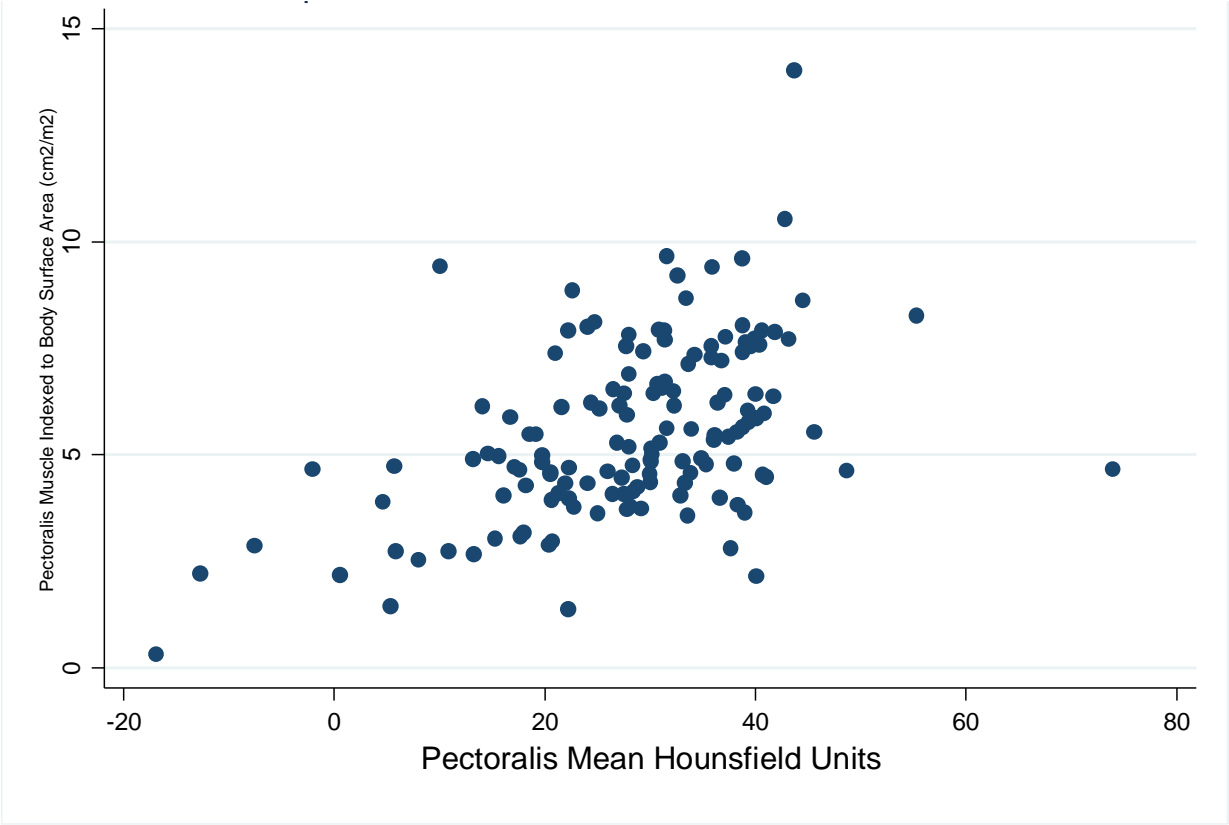
**Supplementary Figure 2 - Distribution of Pectoralis Muscle Mean Hounsfield Unit Measures**



Distribution of unilateral pectoralis muscle mean hounsfield units (PHU<sub>m</sub>).

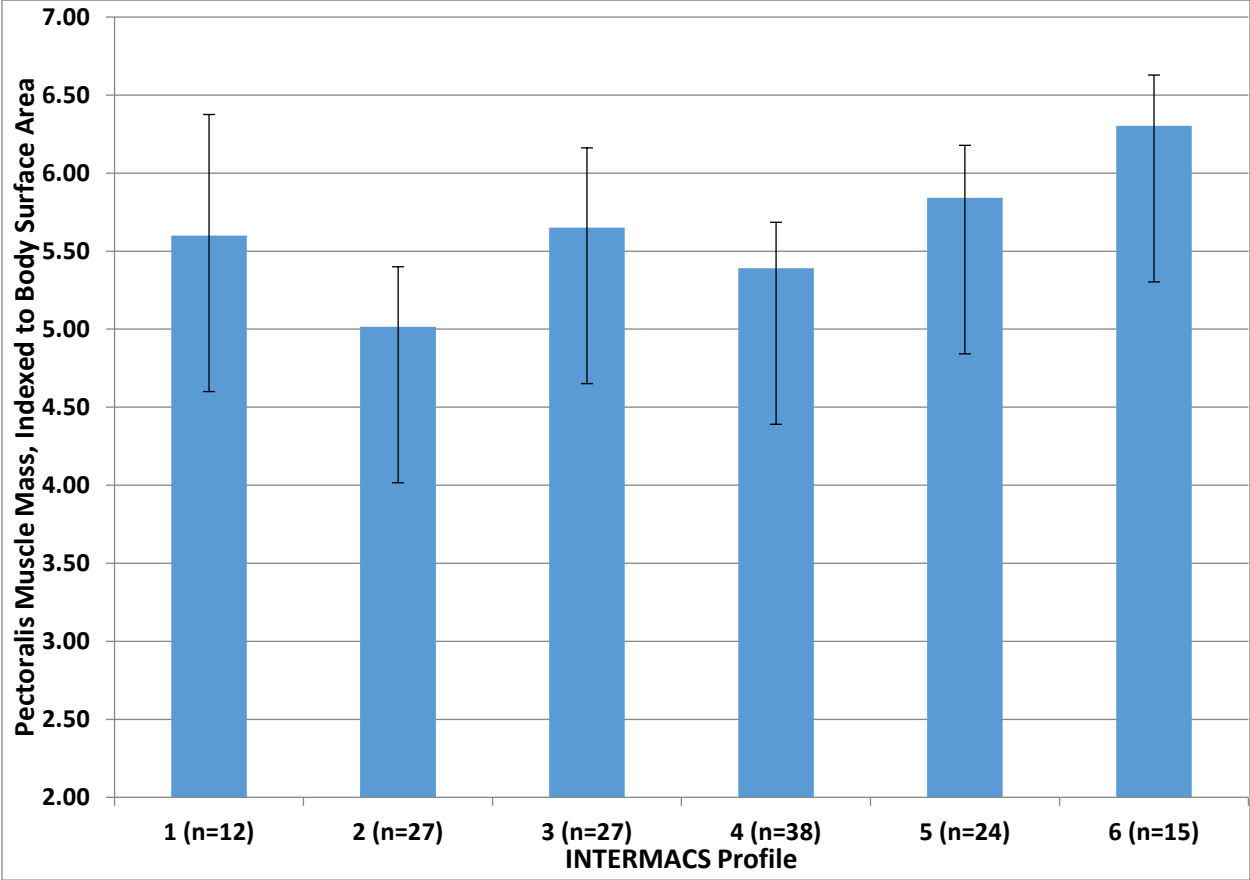


**Supplementary Figure 3 - Relationship Between Pectoralis Muscle Mass and Hounsfield Units**



Pectoralis muscle measurements of cross-sectional area indexed to body surface area ( $\text{cm}^2/\text{m}^2$ ) and mean hounsfield unit measurements were correlated with one another ( $R = 0.47, p < 0.0001$ )

**Supplementary Figure 4A** – Mean Pectoralis Muscle Cross-sectional area indexed to body surface area, by INTERMACS Profile



Supplementary Figure 4B – Mean Pectoralis Hounsfield Units, by INTERMACS Profile

