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Mechanical circulatory support costs in children bridged to heart transplantation – Analysis of a linked database

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Abstract

Background—Pediatric mechanical circulatory support (MCS) has evolved considerably over the past decade. Though marked improvements in waitlist survival have been realized, costs have not been reassessed. This project aimed to assess contemporary MCS costs in children bridged to heart transplant (HT).

Methods—All pediatric HT recipients (2002–2016) were identified from a unique, linked PHIS/SRTR dataset. Costs were calculated from hospital charges, inflated to 2016 Dollars and adjusted for patient-specific characteristics using generalized linear mixed-effects models. Costs and length of stay (LOS) were compared across support strategies at the time of HT (no MCS, VAD, or ECMO) with select subgroup analyses.

Results—A total of 2873 pediatric HT recipients were included; no MCS: 2268 (78.9%), VAD: 470 (16.4%), and ECMO: 135 (4.7%). Both VAD and ECMO were associated with greater total hospitalization costs compared to no MCS ($755,345 and $808,771 vs. $457,086; $p<0.001$). Total costs and LOS were similar between VAD and ECMO groups; however, costs and LOS were greatest for VAD-supported patients in the pre-HT period and greatest for ECMO-supported patients post-HT. Post-HT costs and LOS were similar between patients who did not require MCS

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Disclosures

None

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and those supported with a VAD ($324,887 and 18 days vs. $329,198 and 18 days respectively, p=NS). Outpatients with VAD support at HT demonstrated significantly lower total costs compared to those who were inpatient with continuous flow devices ($552,222 vs. $663,071, p=0.003).

Conclusions—MCS as a bridge to HT in children is associated with greater total costs. While costs are similar between VAD and ECMO groups, the majority of costs associated with VAD support is incurred pre-HT while ECMO costs are incurred primarily post-HT. Discharging patients on VAD support awaiting HT may represent a strategy to reduce costs in this population.

Keywords

Pediatric; heart transplantation; cost; mechanical circulatory support

Introduction

Mechanical circulatory support (MCS) strategies to bridge children to heart transplant (HT) have evolved considerably over the past decade. Ventricular assist device (VAD) use in children has increased,[1] and this shift has contributed to improvements in waitlist survival and post-HT outcomes. [2–4] However, VAD support is known to be very resource intensive. [5–8] Mahle and colleagues reported an average hospitalization cost of $758,199 (in 2007 US dollars) for children bridged to HT with a VAD between 2002 and 2007. [8] Interval improvements in candidate and device selection, patient management, detection of device complications, and an increased emphasis on outpatient management may have shifted these costs. In fact, since the prior report from Mahle *et al.* there has been a marked increase in the use of continuous flow VADs in pediatric patients and a greater emphasis on rehabilitation following VAD placement. [1, 9] In addition to this, improvements in waitlist mortality, in part due to the success of MCS, without a concurrent increase in the number of pediatric donors [10] has likely resulted in increased waitlist times. This may lead to longer durations of MCS prior to HT, further impacting costs.

The aim of this study was to utilize a novel linkage between the Scientific Registry of Transplant Recipients (SRTR) and the Pediatric Health Information System (PHIS) databases to report contemporary cost and length of stay (LOS) data for children bridged to HT with either VAD or extracorporeal membrane oxygenation (ECMO), compared to patients who did not require MCS.

Methods

This study utilized data from the SRTR and the PHIS databases. The SRTR data system includes data on all donors, wait-listed candidates, and transplant recipients in the U.S., submitted by the members of the Organ Procurement and Transplantation Network (OPTN). The Resources and Services Administration, U.S. Department of Health and Human Services provides oversight to the activities of the OPTN and SRTR contractors. The SRTR database includes data from every organ transplant and waitlist addition within the U.S. since October 1987. The PHIS database is an administrative database that collects clinical and daily resource utilization data for hospital encounters from 49 tertiary care children's

hospitals. Hospital encounters captured by the PHIS database include inpatient hospitalizations, observation, ambulatory surgery, and emergency department visits. The SRTR and PHIS databases were linked at the patient level using indirect identifiers (hospital, date of birth, sex, and date of transplant). A total of 3188 unique transplants were identified as being present in both databases and amenable to linkage. Of these, 3057 (95.9%) were uniquely linked and 2896 (90.8%) had complete cost data. [11]

All pediatric (<21 years) HT recipients with available hospital charge information in the linked database were included (2002 – 2016). Hospital charges were converted to costs using year-specific and hospital-specific cost-to-charge ratios. All costs were adjusted for inflation to 2016 U.S. dollars using the medical component of the Consumer Price Index. Costs were assessed for the entire transplant hospitalization and then separately for the pre- and post-HT periods. Costs were adjusted for clinical characteristics and severity of illness at the time of HT using generalized linear mixed effects models with a random hospital intercept. Variables included in the cost adjustment model were selected a priori to account for severity of illness and patient demographics thought to impact hospitalization costs. Variables included in the adjustment model were patient age, underlying cardiac diagnosis, race, blood type, hospital, ECMO support at HT, VAD support at HT, ventilator support at HT, inotropic support at HT, ICU length of stay post-HT, ECMO support post-HT, the need for dialysis post-HT, and transplant year. Since costs are not normally distributed, we modeled the natural log of actual costs. Adjusted model results were then transformed back to the original cost scale for interpretation.

HT recipients were divided into three groups based on MCS requirement (from SRTR data) at the time of HT: no MCS, VAD, or ECMO. Baseline demographics were compared across MCS groups using the chi square test or Kruskal-Wallis test, as appropriate. Unadjusted and adjusted total, pre-, and post-HT hospitalization costs were compared across MCS groups using the Kruskal-Wallis test or Wilcoxon rank sum test, as appropriate. Given the significant variation in cost based on underlying cardiac diagnosis,[11] and the potential for differing MCS strategies in patients with cardiomyopathy and congenital heart disease (CHD), the analysis was repeated after stratifying by diagnosis. For patients with CHD, pre-HT cardiac surgery during the transplant hospitalization was documented using ICD procedure codes available in PHIS (Appendix A). To account for the impact of varying hospital LOS, average daily pre-HT costs were calculated and compared based on pre-HT MCS strategy. Costs were also assessed across MCS groups based on area of spending including pharmacy, laboratory, imaging, supply, clinical, and other (primarily room and nursing charges) costs. For those on VAD support, costs were also analyzed on the basis of pulsatile vs. continuous flow device type and left ventricular or biventricular support. Additionally, given potential variations in post-HT mortality based on pre-HT MCS, the analysis was repeated after stratifying by survival to hospital discharge. All statistical analyses were performed in SAS version 9.4 (SAS Institute; Cary, NC) or STATA version 13 (StataCorp LLC; College Station, TX) with $p<0.05$ considered statistically significant. This project was approved by the Vanderbilt University Institutional Review Board, SRTR, and PHIS.

Results

A total of 2896 pediatric HT recipients were identified in the linked database. Of these, 23 patients were excluded due to use of both ECMO and VAD support at the time of HT with an unclear temporal relationship between the modes of support. Demographics for the 2873 patients included in the analysis are shown in Table 1. A total of 2268 (78.9%) received HT with no MCS, 470 (16.4%) from VAD support, and 135 (4.7%) from ECMO support. The median time on ECMO prior to transplant was 8 days (IQR 4 – 14 days) with 50 days representing the longest duration of pre-HT ECMO support. Patients supported with ECMO at the time of HT were more likely to be younger, require ventilator support at HT, require post-HT iNO, and require dialysis after HT compared to both other groups. Patients supported with ECMO at HT also demonstrated an increased incidence of stroke compared to unsupported patients and were more likely to have prolonged mechanical ventilation post-HT and longer ICU LOS as compared to the no MCS and VAD groups. Patients supported with a VAD at HT were more likely to have a diagnosis of cardiomyopathy, a positive crossmatch, and less likely to require inotropic support at HT compared to other groups.

LOS varied significantly across MCS groups (Table 1). Total LOS was significantly shorter for the no MCS group compared to patients supported with either VAD or ECMO at the time of HT (median: 44 days vs. 78 and 68 days respectively, $p<0.001$ for both). However, there was no significant difference in total LOS between VAD and ECMO groups ($p=0.129$). VAD supported patients demonstrated the longest pre-HT LOS compared to the no MCS and ECMO groups (median: 50 days vs. 18 and 20 days respectively, $p<0.001$ for both). Conversely, patients supported with ECMO had the longest post-HT LOS (median: 37 days vs. 18 days, $p<0.001$ for both).

Costs based on MCS strategy are shown in Table 2. Median total adjusted costs were not significantly different between patients on VAD support at HT and those on ECMO support ($p=0.292$). However, both were significantly higher compared to the no MCS group ($p<0.001$ for both). From admission to HT, costs were highest for patients supported with a VAD, with median adjusted pre-HT costs of $420,636. This was significantly higher compared to the no MCS and ECMO groups with pre-HT costs of $124,019 and $252,497 respectively ($p<0.001$ for both). Costs incurred from the time of HT to discharge were greatest for patients supported with ECMO at the time of HT, with median adjusted post-HT costs of $540,540 ($p<0.001$ compared to both other groups). These results remained unchanged when ICU length of stay was excluded from the cost-adjustment model. Post-HT costs increased with more prolonged duration of pre-HT ECMO support, but this did not reach statistical significance (<1 week: $517,142, 1–2 weeks: $552,958, >2 weeks: $668,562; $p=0.293$). Post-HT costs were not significantly different between those supported with VAD at HT and those who did not require MCS ($329,198 vs. $324,887, $p=0.588$).

Costs based on MCS strategy stratified by underlying diagnosis are shown in Table 3. All costs were significantly higher for patients with a diagnosis of CHD compared to those with cardiomyopathy. Of patients with a diagnosis of CHD, 345 (25.3%) had pre-HT cardiac surgery during the transplant hospitalization. Total costs for CHD patients remained significantly higher than those with cardiomyopathy when excluding those who underwent

prior cardiac surgery ($507,653 vs. $484,744, p<0.001). For both groups, either VAD or ECMO support at HT significantly increased total hospitalization costs compared to patients who were not on MCS at HT, but there was no significant difference in total hospital costs between patients supported with VAD or ECMO, regardless of diagnosis. Pre-HT costs were significantly higher for patients requiring VAD support at HT for both cardiomyopathy and CHD patients when compared to other forms of support. When stratifying the analysis based on diagnosis, VAD-supported patients demonstrated higher post-HT costs compared to patients who did not require MCS; however, post-HT costs for VAD patients remained significantly less compared to patients on ECMO at the time of HT.

Average daily pre-HT costs are shown in Table 4. Both ECMO and VAD supported patients have increased daily pre-HT costs compared to unsupported patients and this remained consistent across diagnoses. There was no significant difference in daily pre-HT costs between patients supported with a VAD and those requiring ECMO support.

The breakdown of total, pre-HT, and post-HT costs based on area of spending are shown in Figures 1a, 1b, and 1c. Compared to patients not on MCS at HT, patients requiring VAD support have increased total and pre-HT costs across all areas of spending including pharmacy, laboratory, imaging, supply, clinical, and other costs. Post-HT costs for VAD supported patients were similar to patients who were not on MCS at HT for laboratory, imaging, supply, and clinical costs, but VAD supported patients demonstrated higher post-HT pharmacy ($27,944 vs. $24,271, p<0.001) and other costs ($75,978 vs. $69,514, p=0.002) compared to patients not requiring MCS. Patients requiring ECMO support have lower pre-HT pharmacy, imaging, supply, clinical, and other costs compared to VAD patients, but demonstrate increased post-HT costs across all spending areas.

Costs stratified by VAD type (pulsatile vs. continuous flow and left ventricular support vs. biventricular support) are shown in Table 5. Pulsatile devices were present in 291 (61.9%) and continuous flow devices were used in 128 (27.2%) patients. Data was insufficient to classify VAD type in 51 (10.9%) patients. Berlin EXCOR (Berlin Heart; Berlin, Germany) was the most common pulsatile device used (N=241) and HeartWare HVAD (HeartWare; Framingham, MA) was the most common continuous flow device (N=83). Use of pulsatile VADs was associated with higher total and pre-HT costs compared to continuous flow devices ($802,081 and $471,315 vs. $645,452 and $333,745 respectively, p<0.001 for both). Post-HT costs were not significantly different between groups (pulsatile: $328,443 vs. continuous flow: $308,025, p=0.181). Median adjusted costs associated with the use of the Berlin EXCOR device were $839,027, $511,959, and $333,680 for the total, pre-HT, and post-HT hospitalization, respectively. Median adjusted costs associated with the use of the HeartWare HVAD device were $600,233, $297,372, and $293,497 for the total, pre-HT, and post-HT hospitalization, respectively. Median total cost associated with VAD equipment was $110,857 for pulsatile and $92,744 for continuous flow devices. There was no significant difference in total or pre-HT costs between patients receiving only left ventricular support and those who received biventricular support. However, post-HT costs were greater for patients receiving biventricular support ($378,736 vs. $317,481, p=0.047). Median total cost associated with VAD equipment was $83,844 for patients with left ventricular support and $158,600 for patients receiving biventricular support.

A total of 70 (14.9%) VAD patients were outpatient prior to HT. Total LOS was not significantly different between outpatients with no MCS and those supported with continuous flow devices (median: 15 days vs. 14 days respectively, p=0.890). Patients supported with continuous flow VAD's who were outpatient at the time of HT demonstrated significantly lower total costs compared to those who were inpatient ($552,222 vs. $663,071, p=0.003).

A total of 2716 (94.5%) patients survived to hospital discharge. Of the 157 patients who died prior to discharge, 109 (69.4%) did not require MCS at HT, 13 (8.3%) were supported with a VAD, and 35 (22.3%) were supported with ECMO. Patients supported with ECMO at HT were significantly more likely to have in-hospital mortality following HT (p<0.001). Total, pre-, and post-HT costs were significantly higher for patients who died compared to those who survived to hospital discharge, regardless of pre-HT MCS. When the analysis was limited to patients who survived to hospital discharge, the findings were unchanged from the primary analysis. In this subgroup analysis, post-HT costs for patients supported with a VAD were no different compared to patients not on MCS at HT ($325,414 vs. $317,559, p=0.359) and both were significantly less than patients supported with ECMO at HT ($517,142, p<0.001 compared to VAD and no MCS groups).

Discussion

We report contemporary cost data for children bridged to HT with VAD or ECMO from the largest U.S. cohort to date. VAD and ECMO both significantly increase total hospitalization costs in children undergoing HT compared to patients not on MCS. Though total costs and LOS were not significantly different between patients on VAD or ECMO at HT, the differences in the distribution of costs and LOS across the pre- vs. post-HT periods were significant. The costs associated with VAD support are incurred primarily in the pre-HT period, while patients supported with ECMO demonstrate increased post-HT costs. Patients supported with ECMO at HT demonstrated significantly shorter pre-HT LOS, suggesting that this was a select group of patients that was fortunate enough to receive a donor organ in a timely fashion. While VAD supported patients demonstrate significantly higher pre-HT costs, we believe this is most likely attributable the successful use of VADs to enable a longer duration of support, as the average daily cost pre-HT was similar between VAD and ECMO groups. Following HT, VAD supported patients had similar post-HT costs and LOS compared to patients who did not require MCS at HT. This is consistent with prior reports demonstrating that VAD support effectively mitigates the severity of illness in children bridged to HT.[12]

It is not surprising that patients requiring VAD support demonstrated increased pre-HT costs compared to the other groups as VAD support is known to be expensive. [5–8] In fact, our analysis demonstrates that patients who are bridged to HT with a VAD have increased pre-HT costs across all areas of spending including increased pharmacy, laboratory, imaging, supply, clinical, and other costs. So while device acquisition costs represent a large expenditure, the increased cost associated with VAD support is not solely attributable to the cost of the devices alone. The finding that average daily pre-HT costs were not significantly

different between the VAD and ECMO groups, suggests that duration of inpatient support may be driving the pre-HT cost difference observed.

When the entire cohort was analyzed, patients supported with a VAD demonstrated similar post-HT costs compared to unsupported patients. However, when stratified by diagnosis, the VAD group had significantly higher post-HT costs. This finding likely reflects the overall increased costs in the CHD population in conjunction with decreased VAD utilization in this group, thereby increasing the costs of the unsupported group relative to the VAD population when the entire cohort was analyzed. It also highlights the need to consider separating patients with cardiomyopathy from those with CHD for analysis, as has been noted in prior studies. [13, 14] Importantly, despite a small increase in post-HT costs incurred by patients requiring VAD support compared to unsupported patients, post-HT costs for VAD patients remained significantly lower than those on ECMO at the time of HT.

Our analysis provides benchmark VAD costs based on device type. The Berlin EXCOR was the most common pulsatile device and costs were greater compared to continuous flow devices. While device acquisition costs may differ between the Berlin EXCOR compared to continuous flow devices, there are multiple reasons why overall costs may be greater. Pulsatile VADs are more likely to be used in younger patients, a group that has been demonstrated to have higher overall costs. [11] Pulsatile devices are also associated with more device complications,[15–18] which may necessitate pump exchanges and lead to additional interventions. Lastly, continuous flow devices are more amenable to discharging patients from the hospital. Given that a large proportion of VAD costs are incurred during the pre-HT period, patient discharge while awaiting HT represents a cost-saving strategy. Adults are now routinely discharged following VAD placement [19] and there is increasing experience with this in the pediatric population. [20–22] In fact, 70 patients in our analysis on VAD support were outpatient prior to transplantation. Importantly, this group demonstrated significantly lower total costs compared to patients supported with continuous flow devices that were inpatient at the time of HT. This suggests that as the practice of discharging pediatric patients supported with a VAD expands, the costs associated with pediatric VAD support may decrease.

Prior reports on the costs associated with MCS as a bridge to HT in children are limited. Morales, *et al.* reported total hospitalization costs of $174,743 in 187 pediatric patients who underwent VAD placement in 2006. [23] However, only 26% of their cohort was bridged to HT and therefore the results cannot be directly compared with the findings of our analysis. A separate analysis by Mahle *et al.*, reported a mean hospitalization cost of $758,199 (in 2007 U.S. dollars) for 94 children bridged to HT with a VAD between 2002 and 2007. [8] While this result is comparable to our findings, it describes an earlier cohort, where use of continuous flow devices was less common. [1] This report also describes mean costs, a likely biased estimate given that costs are not normally distributed. [24, 25] For this reason, we reported median costs associated with the use of MCS in the present analysis. With respect to ECMO support to HT, multiple prior reports have documented a relatively high cost, [26, 27] with one group showing that it does not meet the conventionally applied criteria for cost-effectiveness as a bridge to HT in children. [27]

Our analysis has several limitations. A significant percentage of patients with CHD underwent cardiac surgery prior to HT, resulting in overestimation of costs that are not directly attributable to MCS. There is an inherent selection bias in our cohort. The decision regarding MCS is based on multiple factors and patients who received ECMO support may not have been suitable candidates for VAD placement. As evidence of this, in our analysis a higher portion of patients with hypertrophic cardiomyopathy, restrictive cardiomyopathy, and single ventricle anatomy received support with ECMO as opposed to a VAD. There are also likely differences across groups based on severity of illness. While our analysis attempted to account for this, there are likely factors not captured within the linked dataset that could not be adjusted for. The linked PHIS and SRTR database only includes transplanted patients and therefore excludes patients who were listed but not transplanted. The impact on our analysis of excluding patients requiring MCS who did not undergo transplantation is unknown, but represents an additional selection bias. Children bridged to transplant with a VAD have been shown to have higher costs relative to children with VADs who die on the waitlist and those who undergo successful device explant. [8] Therefore, exclusion of these patients likely biases our analysis toward higher costs and LOS estimates for VAD patients. In addition to this, patients supported with ECMO are less likely to survive to HT [28] and therefore our cohort of patients on ECMO at HT is a select group with short waitlist times, potentially underestimating costs of ECMO support by excluding patients who had longer waitlist durations but did not survive until HT. Patients supported with ECMO at HT also have a much higher incidence of post-HT mortality, potentially impacting our analysis. However, the results of our analysis did not change when patients who died prior to hospital discharge were excluded, suggesting that our findings are not attributable to differences in post-HT mortality between MCS groups. Also, the PHIS database does not include physician professional fees, thereby underestimating a small proportion of costs. As expected with any large dataset, missing and erroneous data can be problematic. While merger of these databases helps to improve data granularity, it is often not possible to reconcile discrepancies that may occur between datasets.

Conclusion

Our analysis provides contemporary cost and LOS data for the use of MCS as a bridge to HT in children from the largest U.S. sample to date. MCS as a bridge to HT in children is associated with greater costs during the entire HT hospitalization relative to children without MCS. VADs enable a longer duration of support which results in increased pre-HT costs, but effectively minimizes post-HT resource utilization. Discharging patients on VAD support awaiting HT represents a strategy to reduce costs in this population.

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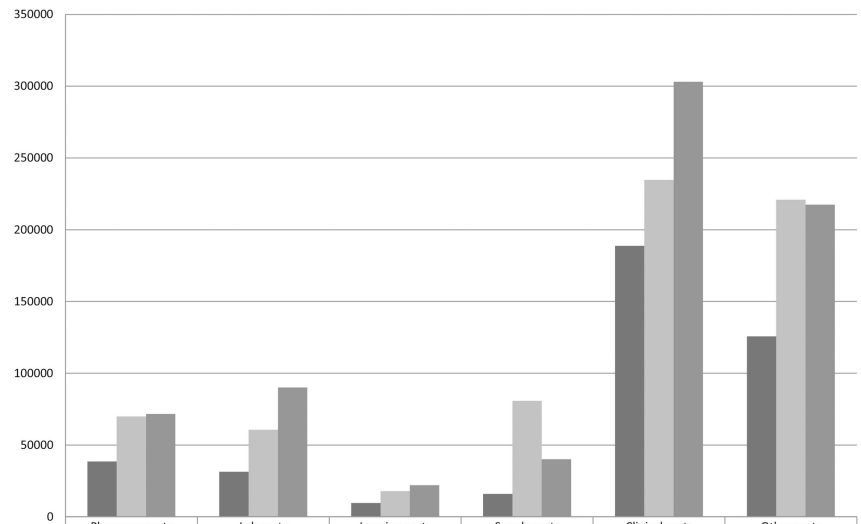
Appendix A. ICD codes defining prior cardiac surgery

ICD-10 Procedure Codes			
021K0JP	02HK0JZ	02RW0KZ	02UW0KZ
021V0ZQ	02HL02Z	02SP0ZZ	02VP0CZ
021W0JQ	02HL0JZ	02SW0ZZ	02VQ0CZ
021W0KP	02LR0ZT	02U50JZ	02VR0CT
027R0DT	02PA0JZ	02UF0JZ	02VR0CZ
02B50ZZ	02PA0MZ	02UG0JZ	02WAXRZ
02BH0ZZ	02PA0QZ	02UJ0JZ	02WY07Z
02BL0ZX	02PA0RZ	02UL0JZ	03LH0ZZ

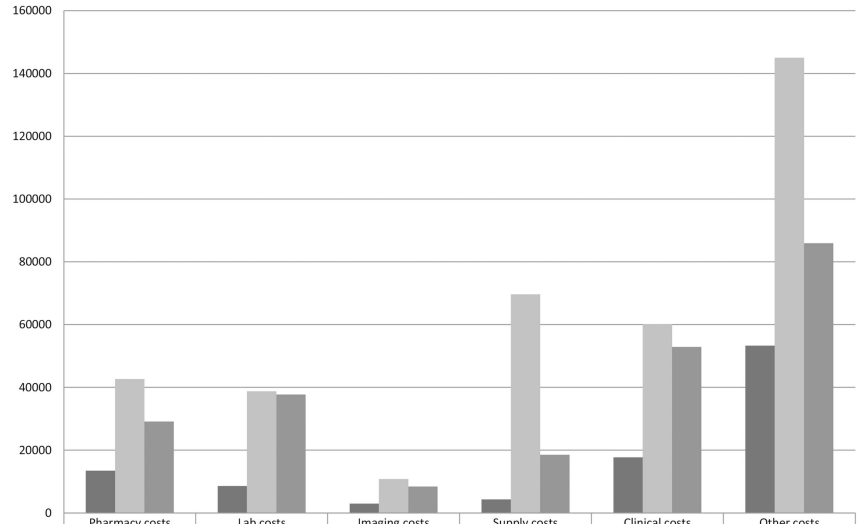
ICD-10 Procedure Codes				
02BN0ZZ	02PY0JZ	02UM07Z	03QH0ZZ	
02BS0ZZ	02Q50ZZ	02UN0JZ	05L00ZZ	
02BT0ZZ	02QF0ZZ	02UP07Z	06U007Z	
02BW0ZZ	02QM0ZZ	02UQ07Z	0JH606Z	
02CK0ZZ	02QP0ZZ	02UQ0KZ	0JH60XZ	
02CL0ZZ	02QQ0ZZ	02UR0JZ	0W3C0ZZ	
02H60JZ	02QR0ZZ	02UR0KZ	0WCD0ZZ	
02H70MZ	02QW0ZZ	02UV07Z	0WPD0YZ	
02HA0QZ	02RP0KZ	02UV0KZ	3E080GC	
02HA0RZ	02RQ08Z	02UW07Z		
ICD-9 Procedure Codes				
35.10	35.39	35.99	37.49	38.45
35.11	35.51	36.03	37.52	38.64
35.12	35.53	36.11	37.53	38.65
35.13	35.61	36.15	37.54	38.7
35.14	35.62	36.19	37.55	38.85
35.21	35.63	36.2	37.60	39.0
35.22	35.71	36.31	37.63	39.21
35.23	35.72	36.91	37.64	39.23
35.24	35.73	36.99	37.65	39.29
35.25	35.81	37.10	37.66	39.54
35.26	35.82	37.11	37.74	39.61
35.27	35.83	37.12	37.91	39.62
35.28	35.84	37.24	37.99	39.64
35.31	35.91	37.31	38.04	
35.33	35.92	37.33	38.05	
35.34	35.94	37.36	38.34	
35.35	35.95	37.41	38.35	

a

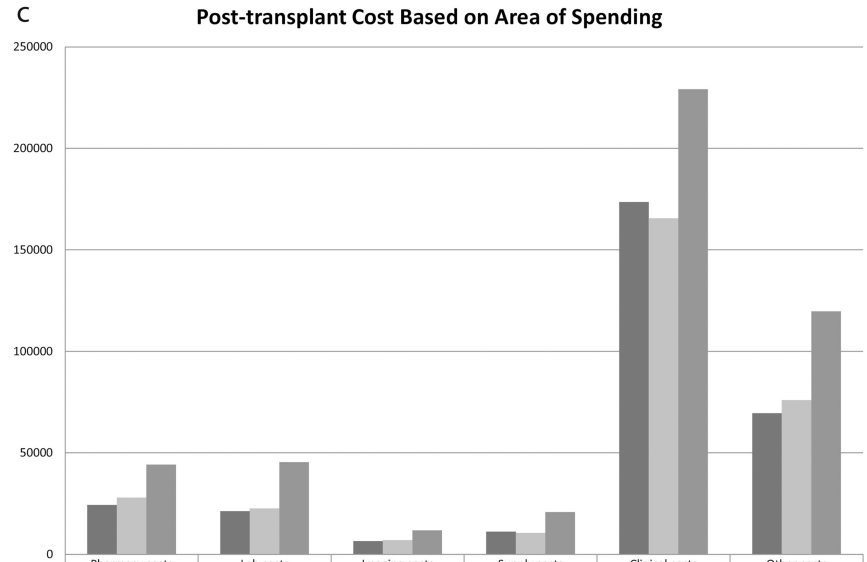


	Pharmacy costs	Lab costs	Imaging costs	Supply costs	Clinical costs	Other costs
No MCS	38482.24	31384.11	9558.351	15927.3	188757.4	125615.5
VAD	69874.02	60634.91	17820.97	80743.05	234639.2	220816.8
ECMO	71656.51	90101	22051.83	40085.89	303060.2	217425.1

b



	Pharmacy costs	Lab costs	Imaging costs	Supply costs	Clinical costs	Other costs
No MCS	13469.3	8562	2968	4303.9	17735.3	53318.3
VAD	42672.6	38784.9	10801.2	69642.6	60106.3	145029.6
ECMO	29137.9	37754.6	8413.7	18555.8	52891.3	85926.3



	Pharmacy costs	Lab costs	Imaging costs	Supply costs	Clinical costs	Other costs
No MCS	24270.87	21232.62	6489.027	11135.52	173610.6	69514.16
VAD	27944.08	22596.45	6970.824	10516.47	165574.2	75978.41
ECMO	44185.46	45434.78	11818.76	20823.27	229153.5	119757.5

Figure 1.

Cost based on area of spending for a) Total, b) Pre-transplant, and c) Post-transplant hospitalization. * Other costs consist primarily of room and nursing charges.

Table 1

Demographics based on MCS

	Total N=2873		None N=2268 (78.9%)		VAD N=470 (16.4%)		ECMO N=135 (4.7%)		p-value[a]
Age									
<1 year	892	(31.1%)	729	(32.1%)	77	(16.4%)	86	(63.7%)	
1–5 years	681	(23.7%)	525	(23.2%)	130	(27.7%)	26	(19.3%)	
6–10 years	401	(14.0%)	326	(14.4%)	67	(14.3%)	8	(5.9%)	<0.001
11–17 years	823	(28.7%)	626	(27.6%)	184	(39.2%)	13	(9.6%)	
18–21 years	76	(2.7%)	62	(2.7%)	12	(2.6%)	2	(1.5%)	
Diagnosis									<0.001[b]
Cardiomyopathy	1318	(46.4%)	899	(40.1%)	373	(80.2%)	46	(34.3%)	
Dilated Cardiomyopathy	1047	(79.4%)	659	(73.3%)	350	(93.8%)	38	(82.6%)	
Restrictive Cardiomyopathy	154	(11.7%)	142	(15.8%)	9	(2.4%)	3	(6.5%)	<0.001[c]
Hypertrophic Cardiomyopathy	79	(6.0%)	71	(7.9%)	5	(1.3%)	3	(6.5%)	
Other Cardiomyopathy	38	(2.9%)	27	(3.0%)	9	(2.4%)	2	(4.4%)	
Congenital Heart Disease	1363	(48.0%)	1193	(53.2%)	85	(18.3%)	85	(63.4%)	0.001[d]
Single Ventricle Lesion	572	(41.9%)	522	(43.7%)	20	(23.5%)	30	(35.3%)	
Retransplant	159	(5.6%)	149	(6.7%)	7	(1.5%)	3	(2.2%)	
Race									
Caucasian	1687	(58.7%)	1362	(60.1%)	237	(50.4%)	88	(65.2%)	
African-American	531	(18.5%)	400	(17.6%)	112	(23.8%)	19	(14.1%)	0.002
Hispanic	491	(17.1%)	379	(16.7%)	94	(20.0%)	18	(13.3%)	
Other	164	(5.7%)	127	(5.6%)	27	(5.7%)	10	(7.4%)	
Male Sex	1570	(54.7%)	1216	(53.6%)	270	(57.5%)	84	(62.2%)	0.061
Blood Type									
O	1298	(45.2%)	998	(44.0%)	240	(51.1%)	60	(44.4%)	
A	1079	(37.6%)	877	(38.7%)	155	(33.0%)	47	(34.8%)	0.109
B	373	(13.0%)	297	(13.1%)	57	(12.1%)	19	(14.1%)	
AB	123	(4.3%)	96	(4.2%)	18	(3.8%)	9	(6.7%)	
Ventilator at Transplant	478	(16.6%)	311	(13.7%)	77	(16.4%)	90	(66.7%)	<0.001
Inotropes at Transplant	1426	(49.6%)	1206	(53.2%)	138	(29.4%)	82	(60.7%)	<0.001

	Total N=2873		None N=2268 (78.9%)		VAD N=470 (16.4%)		ECMO N=135 (4.7%)		p-value[a]
Positive Crossmatch (any method)	388	(13.5%)	287	(12.7%)	83	(17.7%)	18	(13.3%)	0.015
Positive Crossmatch (CDC)	143	(5.0%)	104	(4.6%)	34	(7.2%)	5	(3.7%)	0.044
iNO Post-transplant	1438	(50.2%)	1102	(48.7%)	251	(53.4%)	85	(63.0%)	0.002
Total Length of Stay (Days)	50	(20–98)	44	(17–91)	78	(38–131)	68	(40–99)	<0.001
Pre-transplant Length of Stay (Days)	22	(1–62)	18	(1–56)	50	(19–99)	20	(12–46)	<0.001
Post-transplant Length of Stay (Days)	18	(12–32)	18	(11–31)	18	(13–32)	37	(22–57)	<0.001
Outpatient Prior to Transplant	939	(32.7%)	869	(38.3%)	70	(14.9%)	0	-	<0.001
Post-Transplant ICU Days	9	(4–20)	9	(4–20)	8	(4–16)	24	(12–46)	<0.001
Post-Transplant Days on Ventilator	2	(1–8)	2	(1–7)	2	(1–5)	17	(6–37)	<0.001
Post-Transplant Complications									
Dialysis	158	(5.5%)	104	(4.6%)	24	(5.1%)	30	(22.4%)	<0.001
Rejection Prior to Discharge	356	(13.6%)	272	(13.3%)	61	(13.2%)	23	(20.2%)	0.108
Stroke	96	(3.4%)	62	(2.8%)	24	(5.2%)	10	(7.6%)	0.001
Chylothorax	147	(5.1%)	117	(5.2%)	21	(4.5%)	9	(6.7%)	0.582
Cardiac Reoperation	183	(8.1%)	140	(7.8%)	27	(7.9%)	16	(14.0%)	0.061

Continuous variables reported as median (25% – 75%) and categorical variables reported as N(%)

[a] p-values from the chi square test for categorical and Kruskal Wallis test for continuous variables

[b] p-value comparing cardiomyopathy, congenital heart disease, and retransplant

[c] p-value comparing forms of cardiomyopathy based on the presence of mechanical support

[d] p-value comparing single ventricle lesions based on the presence of mechanical support

Table 2

Adjusted total, pre-, and post-transplant hospitalization costs based on MCS strategy

Total Hospitalization Costs	**N (%)**		**Adjusted Costs** [¥]			**p-value** [§]
All patients	2873	(100%)	$509,870	($374,529 -	$752,899)	-
Type of MCS						
None	2268	(78.9%)	$457,086	($347,270 -	$644,527)	<0.001
VAD	470	(16.4%)	$755,345	($580,149 -	$1,059,854)	Ref.
ECMO	135	(4.7%)	$808,771	($572,341 -	$1,157,392)	0.292
Pre-Transplant Costs	N (%)		Adjusted Costs [¥]			p-value
All patients	2873	(100%)	$163,718	($79,772 -	$307,702)	-
Type of MCS						
None	2268	(78.9%)	$124,019	($65,758 -	$222,382)	<0.001
VAD	470	(16.4%)	$420,636	($307,741 -	$628,794)	Ref.
ECMO	135	(4.7%)	$252,497	($161,216 -	$446,178)	<0.001
Post-Transplant Costs	N (%)		Adjusted Costs [¥]			p-value
All patients	2873	(100%)	$330,631	($262,561 -	$448,521)	-
Type of MCS						
None	2268	(78.9%)	$324,887	($258,402 -	$434,268)	0.588
VAD	470	(16.4%)	$329,198	($264,426 -	$442,113)	Ref.
ECMO	135	(4.7%)	$540,540	($391,916 -	$723,485)	<0.001

[§]P-values from the Wilcoxon rank sum test comparing VAD vs. no support and VAD vs. ECMO

[¥]Cost model adjusted for the following variables: Patient age, diagnosis, race, blood type, hospital, ECMO (pre- or post-transplant), VAD, ventilator support, inotropic support, length of ICU stay post-transplant, dialysis post-transplant, and transplant year.

Table 3

Adjusted hospitalization costs based on MCS strategy by diagnosis

Cardiomyopathy						
Total Hospitalization Costs	**N (%)**		**Adjusted Costs** ¥			**p-value** §
All patients	1318	(100%)	$484,744	($340,184 -	$689,643)	-
Type of MCS						
None	899	(68.2%)	$397,726	($304,486 -	$535,694)	<0.001
VAD	373	(28.3%)	$699,220	($560,056 -	$977,340)	Ref.
ECMO	46	(3.5%)	$679,291	($526,415 -	$857,366)	0.256
Pre-Transplant Costs	N (%)		Adjusted Costs ¥			p-value
All patients	1318	(100%)	$168,202	($80,675 -	$328,112)	-
Type of MCS						
None	899	(68.2%)	$110,368	($60,051 -	$196,123)	<0.001
VAD	373	(28.3%)	$401,943	($284,902 -	$575,938)	Ref.
ECMO	46	(3.5%)	$196,768	($125,764 -	$305,497)	<0.001
Post-Transplant Costs	N (%)		Adjusted Costs ¥			p-value
All patients	1318	(100%)	$293,246	($239,532 -	$385,874)	-
Type of MCS						
None	899	(68.2%)	$282,340	($231,569 -	$364,733)	<0.001
VAD	373	(28.3%)	$308,141	($256,566 -	$416,031)	Ref.
ECMO	46	(3.5%)	$476,258	($366,415 -	$610,768)	<0.001
Congenital heart disease						
Total Hospitalization Costs	N (%)		Adjusted Costs ¥			p-value §
All patients	1363	(100%)	$557,435	($415,292 -	$837,336)	-
Type of MCS						
None	1193	(87.5%)	$519,921	($399,902 -	$757,307)	<0.001
VAD	85	(6.2%)	$1,000,163	($693,263 -	$1,472,652)	Ref.

Cardiomyopathy						
Total Hospitalization Costs	**N (%)**		**Adjusted Costs** [¥]			**p-value** [§]
ECMO	85	(6.2%)	$898,993	($646,604 -	$1,273,851)	0.111
Pre-Transplant Costs	N (%)		Adjusted Costs [¥]			p-value
All patients	1363	(100%)	$175,097	($87,460 -	$307,907)	-
Type of MCS						
None	1193	(87.5%)	$155,599	($80,176 -	$264,372)	<0.001
VAD	85	(6.2%)	$561,807	($391,079 -	$903,231)	Ref.
ECMO	85	(6.2%)	$315,634	($195,343 -	$511,169)	<0.001
Post-Transplant Costs	N (%)		Adjusted Costs [¥]			p-value
All patients	1363	(100%)	$373,063	($296,035 -	$517,102)	-
Type of MCS						
None	1193	(87.5%)	$364,171	($291,514 -	$488,149)	0.001
VAD	85	(6.2%)	$404,650	($332,049 -	$591,514)	Ref.
ECMO	85	(6.2%)	$579,937	($466,061 -	$821,927)	<0.001

[§]P-values from the Wilcoxon rank sum test comparing VAD vs. no support and VAD vs. ECMO

[¥]Cost model adjusted for the following variables: Patient age, diagnosis, race, blood type, hospital, ECMO (pre- or post-transplant), VAD, ventilator support, inotropic support, length of ICU stay post-transplant, dialysis post-transplant, and transplant year.

Table 4

Adjusted pre-transplant cost per hospital day based on mechanical circulatory support and diagnosis

	N	%	Pre-transplant cost per hospital day			p-value*
Total (N=2873)						
No MCS	2268	(78.9%)	$5,315	($2,182 -	$20,746)	<0.001
VAD	470	(16.4%)	$8,897	($4,420 -	$21,508)	Ref.
ECMO	135	(4.7%)	$11,796	($5,450 -	$24,810)	0.187
Cardiomyopathy (N=1318)						
No MCS	899	(68.2%)	$4,966	($2,032 -	$14,328)	<0.001
VAD	373	(28.3%)	$8,855	($4,425 -	$22,060)	Ref.
ECMO	46	(3.5%)	$12,024	($5,975 -	$22,513)	0.334
Congenital heart disease (N=1363)						
No MCS	1193	(87.5%)	$5,742	($2,485 -	$24,871)	0.01
VAD	85	(6.2%)	$9,451	($4,326 -	$22,763)	Ref.
ECMO	85	(6.2%)	$11,796	($4,841 -	$25,171)	0.471

*p-values from the Wilcoxon rank sum test

Cost expressed as median (interquartile range), inflated to 2016 dollars

Table 5

Adjusted total, pre-, and post-transplant hospitalization costs based on VAD type

	N	(%)	Median (IQR)			p-value*
Total cost	470	(100%)	$755,345	($580,149 -	$1,059,854)	-
Device Type						
Pulsatile	291	(61.9%)	$802,081	($622,525 -	$1,134,111)	
Continuous Flow	128	(27.2%)	$645,452	($493,864 -	$914,146)	<0.001
Other/Unspecified	51	(10.9%)	$788,114	($572,323 -	$1,174,256)	
Ventricular Support						
LVAD Only	326	(69.4%)	$757,225	($580,018 -	$1,070,857)	
BiVAD	102	(21.7%)	$742,364	($581,739 -	$1,149,024)	0.824
Other/Unspecified	42	(8.9%)	$787,581	($571,696 -	$958,182)	
Pre-transplant costs	470	(100%)	$420,636	($307,009 -	$629,622)	-
Device Type						
Pulsatile	291	(61.9%)	$471,315	($344,898 -	$708,881)	
Continuous Flow	128	(27.2%)	$333,745	($232,198 -	$463,225)	<0.001
Other/Unspecified	51	(10.9%)	$421,844	($284,887 -	$665,486)	
Ventricular Support						
LVAD Only	326	(69.4%)	$435,600	($317,010 -	$650,728)	
BiVAD	102	(21.7%)	$390,890	($282,342 -	$646,520)	0.383
Other/Unspecified	42	(8.9%)	$408,044	($298,648 -	$568,420)	
Post-transplant costs	470	(100%)	$329,198	($264,426 -	$442,113)	-
Device Type						
Pulsatile	291	(61.9%)	$328,443	($269,194 -	$448,250)	
Continuous Flow	128	(27.2%)	$308,025	($260,492 -	$424,569)	0.181
Other/Unspecified	51	(10.9%)	$356,339	($274,761 -	$471,299)	
Ventricular Support						
LVAD Only	326	(69.4%)	$317,481	($262,035 -	$436,904)	
BiVAD	102	(21.7%)	$378,736	($282,637 -	$472,461)	0.047

	N	(%)	Median (IQR)		p-value*
Other/Unspecified	42	(8.9%)	$350,867	($281,315 -	$402,451)

* p-values from the Wilcoxon rank sum test comparing pulsatile to continuous flow VAD and LVAD to BiVAD

Cost expressed as median (interquartile range), inflated to 2016 dollars

Variables included in risk-adjustment model:

Age, diagnosis, race, blood type, hospital, ECMO (pre- or post-transplant), VAD, ventilator, inotropic support, ICU LOS, transplant year, need for dialysis post-transplant