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Effect of Center Catheterization Volume on Risk of Catastrophic Adverse Event Following Cardiac Catheterization in Children

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Abstract

Background—Procedural volume has been shown to be associated with outcome in cardiac catheterization and intervention in adults. The impact of center-level factors (such as volume) and their interaction with subject- and procedure-level factors on outcome following cardiac catheterization in children is not well described. We hypothesized that higher center catheterization volume would be associated with lower risk of catastrophic adverse events.

Methods—We studied children and young adults 0–21 years of age undergoing one or more cardiac catheterizations at centers participating in the Pediatric Health Information Systems (PHIS) database between 2007–2012. Using mixed effects multivariable regression, we assessed the association between center catheterization volumes and the risk of a composite outcome of death and/or initiation of mechanical circulatory support within 1 day of cardiac catheterization adjusting for patient- and procedure-level factors.

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Results—63,994 procedures performed on 40,612 individuals from 38/43 centers contributing data to the PHIS database were included. The adjusted risk of the composite outcome was 0.1%. Increasing annual catheterization lab volume was independently associated with reduced risk of the composite outcome (odds ratio per a 100 procedure/year increment 0.78 (95% CI 0.65–0.93), $p < 0.006$). Younger age at catheterization, previous cardiac operation in the same admission as the catheterization, pre-procedural vasoactive medications, and hemodialysis were also independently associated with an increased risk of adverse outcomes.

Conclusions—Higher cardiac catheterization laboratory volume was associated with reduced risk of catastrophic adverse outcome in the immediate post-catheterization period in children. The observed benefit of catheterization at a larger volume center may be attributable to transmissible best practices or inextricable benefits of larger systems.

Keywords

outcomes research; cardiac catheterization; pediatric cardiology

Introduction

Cardiac catheterization is critical for the diagnosis and treatment of patients with a variety of cardiac conditions. The caseload of a pediatric cardiac catheterization laboratory is comprised of a wide range of diagnoses and procedures in a broad range of patient ages and sizes, which makes defining the risk associated with cardiac catheterization challenging. Single-center case series have reported outcomes over several decades^{1–7}. More recently, based on data from multicenter registries has allowed for production of a risk adjustment model including hemodynamics, patient age, and procedure type^{8–11}. However, low event rates and the small number of centers included have made comparison of outcomes between centers challenging.

Procedural volume has been associated with improved outcomes across many medical and surgical procedures. In studies of coronary angioplasty, both patient-level characteristics and center procedural volume are associated with risk of adverse outcome^{12–17}. In congenital cardiology, center surgical volumes have been associated with improved outcomes^{18–25}, but to date, we are not aware of other studies that have assessed the association of center volume and catastrophic adverse events following cardiac catheterization in children.

Administrative databases provide access to data from multiple centers, allowing for analysis of outcomes while adjusting for covariates. We performed a retrospective multi-center cohort study using data from the Pediatric Health Information Systems (PHIS) database. We hypothesized that increased cardiac catheterization procedural volume would be associated with reduced risk of adverse outcome after adjusting for possible confounders.

Methods

Data Source

The PHIS database is an administrative database that contains data from inpatient, emergency department, ambulatory surgery, and observation encounters from 43 not-for-

profit, tertiary care pediatric hospitals in the United States (Technical Appendix)²⁶. A data-use agreement was signed with CHA. The institutional review board of The Children's Hospital of Philadelphia(CHOP) reviewed the proposed project and determined that it did not represent human subjects research in accordance with the Common Rule (45 CFR 46.102(f)).

Study Population

We included children and adults of age 0–21 years undergoing cardiac catheterization, as identified by International Classification of Disease, ninth revision code (ICD-9): 37.21–37.29), at any of the 43 PHIS centers between 1/1/2007 and 12/31/2012. Encounters in PHIS include inpatient and observation admissions but exclude outpatient procedures (those without overnight observation). It does include subjects who die or undergo ECMO on the date of catheterization following an outpatient procedure. We excluded subjects undergoing electrophysiology studies (ICD-9 codes: 37.2, 37.26, and 37.27), since it was felt the procedure and risk were qualitatively different from diagnostic and interventional cardiac catheterization procedures. We excluded subjects who were already receiving ECMO on prior to the date of catheterization, which is identified in the database. We also excluded subjects from centers 1) reporting fewer than 25 cardiac catheterization procedures per year over the study period or 2) not reporting cardiac catheterization procedures in at least 4 of 6 years during the study period. This was intended to restrict analysis to centers with stable reporting practices and procedural volumes.

Study Measures

Data were extracted from the PHIS database by direct query using ICD-9 codes for diagnoses and procedures as well as Clinical Transaction Codes (CTC) for pharmaceutical products (Supplementary Table 1). The primary exposure was defined as mean annual number of catheterizations performed at the center over the study period. This was chosen over individual annual catheterization volume because it was felt that the experience of an individual center was durable and unlikely to be prone to year-to-year variation. The primary outcome was a composite of death or initiation of mechanical circulatory support (extracorporeal membrane oxygenation, percutaneous ventricular assist device, or balloon pump) on the date of service of catheterization or the following day. Patient-level data included subject age, sex, race, insurance payer (private, public, other), genetic syndrome²⁷, non-cardiac congenital anomalies, history of prematurity (defined as gestational age<34 weeks in patients less than 1 year of age), cardiac diagnoses (congenital heart disease in isolation, congenital heart disease with pulmonary hypertension, pulmonary hypertension without congenital heart disease, myocarditis, cardiomyopathy, and orthotopic heart transplantation (OHT)), location of patient prior to the procedure (outpatient, NICU, ICU, CICU, and step down unit/cardiac unit), receipt of mechanical ventilation prior to catheterization, receipt of inotropic agents, systemic vasodilators, and pulmonary vasodilators. Procedural data included whether a trans-catheter intervention was performed during the case. Center-level data included center average annual catheterization and cardiac operative volume over the study period²⁸. Outcome data collected included in-hospital death, initiation of extracorporeal membrane oxygenation, and length of stay.

Statistical Analysis

Descriptive statistics were expressed as mean $\pm$ standard deviation, median (range and inter-quartile range (IQR)), and percentages and counts as appropriate. Centers were divided into quintiles based on mean annual center catheterization volume over the study period.

Comparisons of quintile characteristics were made using Kruskal-Wallis and Chi-squared tests. Multiple catheterizations were performed on individual subjects over the study period. All eligible procedures were included, and all statistics are reported per procedure not per individual subject except where noted. As noted below, attempts were made to account for the bias introduced by multiple catheterizations, first through adjustment and later through restriction in a sensitivity analysis.

The association between center volume and composite outcome was assessed using logistic mixed-effects modeling. Adjusted risks of outcomes were estimated using conditional standardization (the risk estimated if variables are set at either the mean values for continuous variables or the referent group for categorical variables) to provide a clinically relevant estimate. No interaction terms were included in the initial model. Post-hoc interactions between 1) operative and catheterization volumes, 2) catheterization volume and trans-catheter intervention were assessed, and 3) between age category and history of prematurity.

Several pre-specified sensitivity and subset analyses were performed. First, the effect of varying the definition of the outcome was assessed: 1) death or ECMO on the same day as catheterization, 2) death within one day of catheterization, 3) death before hospital discharge. We also separately 1) restricted the sample to the first catheterization in the data set, 2) excluded center(s) with annual volume >2 standard deviations from the mean of the study cohort, 3) excluded subjects who underwent catheterization on the same day as a cardiac operation to determine if salvage catheterizations were overly influential on risk (data not shown), and 4) excluded catheterizations following OHT, because of concerns raised that these cases were of low risk and more common at high volume centers and a source of bias (data not shown).

Subjects for whom the date of catheterization was missing were excluded. For pre-identified covariates (such as race and cardiac diagnosis), data were missing in less than 10% of cases. For these subjects, their status was coded as "missing," and included in analysis. There were no other missing data, and 100% of the remaining 63,994 procedures were included in multivariable models.

All analysis was performed using Stata MP v13 (Statacorp, College Station TX). Threshold for statistical significance was set at $p < 0.05$.

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Results

Study population

The initial data query yielded data from 44 centers, with 68,463 procedures performed in 42,219 subjects (Figure 1). Six centers (including 289 (0.4 %) procedures on 241 subjects) were excluded because they failed to meet inclusion criteria. 472 (0.7%) procedures were excluded because of missing date of catheterization and 3,916 (6%) procedures were excluded because the subjects were receiving mechanical circulatory support prior to the day of catheterization. Thus, the study sample included 63,994 procedures in 40,612 unique subjects from 59,945 hospitalizations across 38 centers.

The median age at catheterization was 3.4 years (range: 0 to 21 years) (Table 1). The population was 54% male and 65% white with 42% having private insurance. Sixty-six percent of subjects had congenital heart disease without pulmonary hypertension; other diagnoses are shown in Table 1. Prior to catheterization, 10% were receiving positive inotropes, 7% were receiving systemic vasodilators, and 1% were receiving pulmonary vasodilators. Mechanical ventilation was being used in 7% of subjects. Three percent of subjects had a cardiac surgery prior to catheterization during the same hospitalization, and 34% of procedures included a trans-catheter intervention.

The median catheterization volume of the centers was 264 procedures per year (range: 57–1031, IQR: 189–392), and the mean was 297 ± 171 procedures (Figure 2). The median surgical volume of the centers was 440 procedures (range: 167–1320, IQR: 373–556). Mean catheterization and surgical volumes demonstrated significant correlation ($r^2=0.4$, $p<0.001$). Characteristics of the study population divided into quintiles by ascending catheterization lab volume are shown in Table 2. Higher volume centers had slightly older median age of patients ($p<0.001$), which was largely due to increasing numbers of subjects >18 years of age. They also had a larger percentage of subjects who had received OHT (17% in the largest volume quintile and 9% in the lowest volume quintile). Otherwise, there were no other clearly important trends associated with volume (despite many comparisons having significant p values due to large numbers and high precision).

The risk of the composite outcome within 1 day of catheterization was 3.5% ($n=222$). Of these 17 (0.3%) died, while 206 (3.3%) subjects underwent initiation of mechanical circulatory support, and 1/206 died within 1 day of catheterization after being placed on ECMO.

Center volume and other risk factors for death or mechanical circulatory support within 1 day of catheterization

Table 3 shows the results of a mixed effects multivariate regression model of the risk factors for death or mechanical circulatory support within 1 day after catheterization. Using conditional standardization for other covariates, the adjusted risk of composite primary outcome within one day of catheterization was 0.1% (95% CI: 0.1–0.2%). Higher center

catheterization volume was associated with a lower risk of the composite outcome (OR per 100 procedure/year increase=0.78 (95%CI: 0.65–0.93, $p=0.006$). Thus, the odds ratio for composite outcome at a center with an annual volume of 100 catheterizations was 2.2 (95%CI: 1.7–2.9) compared to a center with a volume of 300 catheterizations. A center which averaged 500 catheterizations per year had an odds ratio of 0.4 (95%CI: 0.3–0.6) for the composite endpoint compared to a center which did 300 catheterizations per year.

Increasing operative volume was associated with increased risk of composite outcome (OR per 100 procedures: 1.14, 95%CI 1.07–1.23, $p<0.001$). There was a significant interaction between center catheterization and operative volume (p for interaction = 0.04) (Figure 3). For a center with a center volume of 100 catheterizations and 100 operations per year, the adjusted risk of composite outcome was 0.14% (95% CI: 0.08–0.23%), for a center with 300 catheterization and 300 operations the risk was 0.11% (95%CI: 0.07–0.16%), and for a center with 500 catheterizations and 500 operations the risk was 0.08% (95%CI: 0.05–0.13%).

Age <30 days and age <1 year were associated with increased risk relative to ages between 1 and 8 years, while risk was progressively reduced in subjects of ages 8–18 years and those >18 years (all $p < 0.001$). A diagnosis of OHT was also associated with lower risk ($p<0.001$). The odds ratios associated with cardiomyopathy and myocarditis were both suggestive of increased risk but were not statistically significant. Accounting for other factors, a history of prematurity was associated with reduced risk of composite outcome (OR: 0.62, $p=0.03$). Race, insurance status, genetic syndrome, and non-cardiac congenital anomalies were not independently associated with increased risk of composite outcome. Cardiac operation performed previously in the same hospitalization was associated with increased risk ($p<0.001$) as was receipt of inotropes ($p=0.009$), systemic vasodilators ($p<0.001$), and hemodialysis ($p<0.001$) prior to catheterization. In contrast, receipt of pulmonary vasodilators was associated with reduced risk of composite outcome ($p=0.04$). Trans-catheter intervention performed during the procedures was associated with reduced risk of composite outcome ($p<0.001$). There was no significant interaction between trans-catheter intervention and annual catheterization volume (p for interaction = 0.24) (Supplementary Table 2).

When the outcome was restricted to death less than or equal to one day after catheterization, there was no association between either catheterization volume (OR per 100 cases of 1.00, 95%CI: 0.75–1.34, $p=1.00$) or surgical volume (OR per 100 cases: 1.02, 95%CI: 0.85–1.23, $p=0.81$) and the outcome, although with only 133 events, power was significantly reduced (Supplementary Table 3). An attempt was made to produce the pre-specified model for composite outcome on the day of catheterization. However, the event rate was quite low, and the model did not converge. Results of subset analysis limited to each subject's first catheterization were similar to the primary analysis (Supplementary Table 4). After excluding centers with extreme numbers of catheterizations, there were no changes from the main analyses (Supplementary Table 5).

In the multivariable model of death prior to discharge, the adjusted risk of death prior to discharge was 1 (95%CI: 0.4–2) death per 100,000 procedures (Supplementary Table 6).

The multivariable model produced identified no association between catheterization volume and death ($p=0.10$). Younger age, African American race, and public insurance were associated with increased odds of death, as were all diagnoses compared to congenital heart disease without pulmonary hypertension. Prematurity, genetic syndrome, non-cardiac structural anomalies, and other disease variables associated with increased severity of illness (e.g., inotropes, etc.) were all independently associated with increased odds of death prior to discharge. Increased center operative volume was associated with increased odds of death prior to discharge (OR: 1.24 per 100 cases, $p=0.001$).

A sensitivity analysis adding an interaction term between age category and history of prematurity was performed (Supplementary Table 7). Risk of composite outcome was increased for neonates (age 0–30 days) without a history of prematurity (OR: 4.77, 95%CI: 3.65–6.23, $p<0.001$), and risk in neonates with prematurity was even higher (OR: 5.53, 95%CI: 3.16–9.66, $p<0.001$). Risk in older infants (age 30 days to 1 year) with no history of prematurity was increased (OR: 3.46, 95%CI: 2.84–4.21, $p<0.001$), but those with a history of prematurity did not have significantly elevated risk (OR: 1.39, 95%CI: 0.74–2.59, $p<0.001$).

In response to concerns regarding the contribution of post-OHT catheterizations on procedural volume and outcome, a sensitivity analysis was performed excluding these subjects, and no change was seen in the observed relationship between center catheterization or surgical volume and composite outcome (data not shown).

Discussion

In this large multi-center retrospective cohort study, we found that greater center cardiac catheterization annual volume was associated with a reduced risk of death or initiation of ECMO in the immediate post-catheterization period. Patient age, diagnosis, and level of medical support prior to catheterization were also associated with outcome. To our knowledge, this study is the first to demonstrate an inverse association between center volume and risk of peri-procedure death or ECMO following cardiac catheterization in children.

Understanding the mechanism or mechanisms underlying the association is vital to translating these findings into improved outcomes. Once such a “high performing” center is identified it may be possible to identify practices that are transmissible to other centers. Dissemination of these practices may be a means of improving outcomes across the field regardless of center volume.

The relationship between higher cardiothoracic operative volume and risk for cardiac catheterization outcomes is provocative. The pattern observed is that the annual surgical volume was directly related to adverse outcome. Even with the observed interaction between the two, however, the increase in risk associated with increased surgical volume was overcome by the larger magnitude protective effect of increasing cardiac catheterization volume. We attempted to determine through sensitivity analysis whether this was related to the utilization of catheterization on the same day as a cardiac operation, which might reflect

higher risk “salvage catheterizations.” In this alternative model the association between either catheterization or surgical volume with outcome were unchanged. Another possibility is that the case-mix of higher operative volume centers has a higher baseline risk and the observed risk represents unmeasured confounding. This deserves greater attention and with increasing access to large clinical registries and databases it may be possible for future studies to investigate this association with more detailed subject level clinical information.

Several observed covariates for our combined outcome were unexpected. Receipt of pulmonary vasodilators was associated with reduced risk of death or initiation of mechanical circulatory support. Prematurity was associated with increased risk of adverse outcome in neonates, but with lower risk of adverse outcome in older infants. It may be that either further granularity (e.g. dividing premature infants by degree of prematurity) or within a narrower population (the population with pulmonary hypertension for the risk associated with pulmonary vasodilator therapy) these factors may be more informative. It is also possible that the indication for catheterization in older premature infants differs from those in premature neonates; further study is warranted.

Performance of a trans-catheter intervention was also associated with reduced risk of composite outcome. This is counter-intuitive but may reflect a number of confounding scenarios (e.g. that successful trans-catheter interventions that improve the course of ill patients are captured more frequently than interventions that are either aborted due to instability or are unsuccessful). In any case, the results are provocative and further research focusing on these specific questions is necessary.

The PHIS database is limited to describing the timing of events by date of service. Therefore, to capture events that occurred within 24 hours of a procedure, the window of analysis had to be expanded to include events that could have occurred on the date of service of the catheterization and the next day. This is a limitation of the database. We acknowledge that some events may not have directly resulted from the procedure itself. Recent retrospective analysis of clinical registry data found that only a fraction of deaths within 30 days of cardiac catheterization were attributable to the catheterization²⁹. Sensitivity analyses were performed to assess this. As the time window from the procedure increased (e.g. death prior to hospital discharge), center-level factors were less clearly associated with outcome, while previously observed associations between patient-level factors remained significant. This suggests that center (and catheterization)-specific factors were more influential in early peri-procedural outcomes.

In reviewing the characteristics of the caseload at centers by volume, it was noted that larger centers performed a higher proportion of catheterizations in recipients of OHT, and concern was raised that a higher proportion of these relatively low risk procedures was a potential source of bias. In addition to including it as a covariate in our initial model, we also performed a sensitivity analysis restricting the analysis to patients without OHT. In this model there was no change in the previously observed association between center volume and risk of composite outcome.

There are several limitations to this study. The level of detail for both patient and procedural level risk stratification is limited in an administrative database. The importance of accounting for both pre-procedural risk of subjects and accounting for the risks of the attempted procedures themselves has been demonstrated in previous studies^{10,11}. Unmeasured confounding could explain the observed results, but only if lower volume centers performed procedures on systematically higher risk patients. The coding of specific trans-catheter procedures in the PHIS database were not detailed enough to attempt procedural risk stratification, but for this to be a source of bias away from the null, smaller centers would have had to perform a larger percentage of higher-risk interventions than larger centers. A second important limitation to acknowledge is that the database is limited to catheterizations from observation and inpatient admissions, and therefore excludes outpatient catheterizations. It does however include patients who die or undergo ECMO following what was initially an outpatient procedure. Thus, though our estimates may underestimate the total number of catheterizations per center, they should accurately capture the number of catastrophic adverse events, leading to (if anything) an over-estimate of the risk of catastrophic adverse events/catheterization. Bias would only explain our results if the proportion of catheterizations that were outpatient versus inpatient varied systematically with center volume (with lower volume centers doing more outpatient catheterizations). Other scenarios would introduce negative bias and would make it harder to demonstrate an association between procedural volume and outcome. Finally, PHIS is limited to primary children's hospitals, which may limit generalizability to other centers (including those that primarily treat adults) that perform catheterization in children.

Conclusion

Increased annual catheterization lab volume was associated with a lower risk of catastrophic adverse event within 1 day of pediatric cardiac catheterization. Other patient- and center-level characteristics strongly affect the risk of adverse outcome. Further research is necessary to determine whether the advantage associated with increasing cardiac catheterization volume is due to transmissible best practices or is an inextricable benefit of larger volume.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1. Study population

Figure 2. Center cardiac operative and cardiac catheterization volumes

The mean annual volume of cardiac operations (black bars) and (inpatient and observation) catheterizations (blue bars) are depicted for each center. Centers are arranged from smallest to largest annual catheterization volume. Though there is moderate correlation ($r^2=0.4$, $p<0.001$), there are several centers with significant disparity between the number of cardiac operations and catheterizations performed.

Figure 3. Adjusted risk of death or initiation of ECMO by catheterization and operative volume
 Three-dimensional surface graph of adjusted risk of composite outcome (y-axis) is plotted against both annual catheterization (x-axis) and cardiac operative (z-axis) volume. Strata of risk are plotted by color.

Table 1

Study population

Centers	38
N	63,994 procedures in 40,612 unique individuals
Age	3.4 years (Range: 0 days to 21 years, IQR: 225 days–10.9 years)
Age group % (n)	
	<30 days 8% (4,891)
	30 days to 1 year 23% (14,769)
	1 year to 8 years 37% (23,974)
	8 years to 18 years 27% (17,256)
	>18 years 5% (3,104)
Female sex % (n)	46% (29,705)
Race % (n)	
	White 65% (41,435)
	Black 14% (8,646)
	Asian 3% (1,631)
	Other 15% (9,433)
	Missing 4% (2,849)
Payer % (n)	
	Private insurance 42% (26,857)
	Public insurance 42% (26,948)
	Other 16% (10,189)
Cardiac diagnoses % (n)	
	CHD without pulmonary hypertension 66% (42,358)
	Orthotopic heart transplant 14% (8,714)
	CHD with pulmonary hypertension 7% (4,449)
	Pulmonary hypertension without CHD 2% (1,416)
	Cardiomyopathy 4% (2,597)
	Myocarditis 0.3% (226)
	Missing 7% (4,234)
Genetic syndrome % (n)	8% (4,912)
Major non-cardiac structural anomaly % (n)	5% (3,292)
Premature infant % (n)	2% (1,508)
Location prior to catheterization % (n)	
	Not inpatient 81% (51,915)
	General inpatient unit 5% (3,489)
	Cardiac inpatient unit 2% (1,209)
	Step-down unit 1% (683)
	Neonatal ICU/intensive care nursery 3% (2,039)
	ICU 7% (4,659)
Medications prior to catheterization % (n)	

Centers	38
N	63,994 procedures in 40,612 unique individuals
Age	3.4 years (Range: 0 days to 21 years, IQR: 225 days–10.9 years)
Inotropes	6% (3,953)
Systemic vasodilators	4% (2,583)
Pulmonary vasodilators	1% (707)
Pre-procedural mechanical ventilation % (n)	7% (4,317)
Pre-procedural dialysis % (n)	0.2% (120)
Cardiac operation preceding catheterization during hospitalization % (n)	3% (1,721)
Intervention performed during case % (n)	34% (21,978)

Abbreviations: CHD: congenital heart disease,, ICU: intensive care unit, IQR: inter-quartile range

Table 2

Subject population characteristics sub-divided by quintiles of catheterization volume

	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5	p
Centers	8	7	8	8	7	
Average case volume	125±33	195±28	268±40	376±21	534±222	
Total cases	5,643	7,844	11,993	17,234	21,280	
Total individual subjects	4,195	5,696	7,785	11,177	11,641	
Age (years)	2 (0–20)	2 (0–20)	3 (0–20)	3 (0–20)	4 (0–20)	<0.0001
	10% (570)	8% (657)	8% (931)	8% (1,393)	6% (1,340)	<0.001
0–30 days	27% (1,533)	27% (2,083)	24% (2,848)	24% (4,051)	20% (4,254)	
30 days to 1 year	35% (1,959)	39% (3,043)	39% (4,725)	36% (6,242)	38% (8,005)	
1 year to 8 years	24% (1,348)	23% (1,776)	25% (3,013)	27% (4,650)	30% (6,469)	
8 years to 18 years	4% (233)	4% (285)	4% (476)	5% (898)	6% (1,212)	
>18 years	46% (2,607)	46% (3,583)	47% (5,616)	46% (7,984)	47% (9,915)	0.58
Female sex % (N)						
Race						
White	60% (3,360)	66% (5,168)	67% (8,043)	58% (10,027)	70% (14,837)	<0.001
Black	17% (942)	12% (916)	13% (1,544)	19% (3,207)	10% (2,037)	
Asian	3% (143)	3% (214)	4% (450)	1% (252)	3% (572)	
Other	20% (1,105)	13% (1,051)	13% (1,558)	16% (2,769)	14% (2,950)	
Missing	2% (93)	6% (495)	3% (398)	6% (979)	4% (884)	
Payor						
Private insurance	30% (1,707)	37% (2,914)	43% (5,200)	33% (5,743)	53% (11,293)	<0.001
Public insurance	57% (3,213)	56% (4,378)	53% (6,343)	38% (6,629)	30% (6,385)	
Other	13% (723)	7% (552)	4% (450)	28% (4,862)	17% (3,602)	
Cardiac diagnoses						
CHD with no pulmonary hypertension	71% (3,993)	77% (6,031)	70% (8,393)	65% (11,162)	60% (12,779)	<0.001
OHT	9% (506)	5% (356)	11% (1,370)	16% (2,788)	17% (3,694)	
CHD with PH	8% (430)	7% (534)	6% (742)	6% (971)	8% (1,772)	
Pulmonary hypertension without CHD	2% (89)	2% (130)	1% (178)	2% (348)	3% (671)	
Cardiomyopathy	4% (216)	3% (274)	4% (486)	4% (669)	4% (952)	
Myocarditis	0.3% (18)	0.6% (46)	0.3% (37)	0.4% (71)	0.3% (54)	

	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5	<i>p</i>
<i>Missing</i>	7% (391)	6% (473)	7% (787)	7% (1,225)	6% (1,358)	
Genetic syndrome	7% (406)	8% (639)	8% (958)	7% (1,128)	8% (1,781)	<0.001
Major non-cardiac structural anomaly	7% (379)	6% (440)	5% (609)	4% (712)	5% (1,152)	<0.001
Premature infant	4% (198)	3% (225)	3% (303)	2% (380)	2% (402)	<0.001
Location prior to catheterization						
<i>Not inpatient</i>	80% (4,496)	82% (6,447)	80% (9,615)	80% (13,715)	83% (17,642)	<0.001
<i>General inpatient unit</i>	4% (221)	6% (478)	6% (712)	6% (1,046)	5% (1,014)	
<i>Cardiac inpatient unit</i>	3% (164)	0.6% (48)	0.8% (99)	1% (233)	3% (665)	
<i>Step-down unit</i>	0.7% (38)	2% (173)	1% (174)	0.8% (145)	0.7% (153)	
<i>Neonatal ICU</i>	5% (276)	3% (235)	4% (425)	3% (591)	2% (512)	
<i>ICU</i>	8% (444)	6% (462)	8% (966)	9% (1,493)	6% (1,294)	
Medications prior to catheterization						
Inotropes	6% (315)	4% (327)	7% (816)	7% (1,160)	6% (1,335)	<0.001
Vasodilators and mixed agents	3% (162)	3% (199)	5% (622)	4% (719)	4% (881)	
Pulmonary vasodilators	0.3% (14)	0.7% (51)	0.7% (85)	1% (178)	2% (379)	
Pre-procedural mechanical ventilation	10% (544)	8% (650)	7% (799)	6% (1,091)	6% (1,233)	<0.001
Pre-procedural dialysis	0.2% (13)	0.2% (12)	0.2% (29)	0.2% (32)	0.2% (34)	0.4
Cardiac operation preceding catheterization during hospitalization	2% (137)	2% (179)	3% (381)	2% (427)	3% (597)	<0.001
Intervention performed during catheterization	28% (1,627)	39% (3,065)	32% (3,789)	32% (5,439)	38% (8,058)	<0.001

Abbreviations: CHD: congenital heart disease, ECMO: extra-corporeal membrane oxygenation, ICU: intensive care unit, OHT: orthotopic heart transplant

Table 3

Results of multivariable mixed effects model assessing risk factors for death or mechanical circulatory support within 1 day of catheterization

		Odds Ratio	95% CI	p
Center catheterization volume (per 100 procedures)		0.78	0.65–0.93	0.006
Center operative volume (per 100 procedures)		1.14	1.07–1.23	<0.001
Interaction between center catheterization and operative volume (per 100 procedures)		1.02	1.00–1.04	0.04
Age				
	<i>0 to 30 days</i>	5.27	4.05–6.86	<0.001
	<i>30 days to 1 year</i>	3.46	2.84–4.22	<0.001
	<i>1–8 years</i>	1	n/a	n/a
	<i>8–18 years</i>	0.54	0.42–0.70	<0.001
	<i>>18 years</i>	0.21	0.11–0.39	<0.001
Diagnosis				
	<i>CHD without pulmonary hypertension</i>	1	n/a	n/a
	<i>Orthotopic heart transplant</i>	0.15	0.10–0.23	<0.001
	<i>CHD with pulmonary hypertension</i>	0.99	0.75–1.31	0.94
	<i>Pulmonary hypertension without CHD</i>	0.88	0.52–1.49	0.63
	<i>Cardiomyopathy</i>	1.37	0.97–1.93	0.07
	<i>Myocarditis</i>	2.05	0.72–5.84	0.18
	<i>Missing</i>	0.89	0.62–1.27	0.51
Race				
	<i>White</i>	1	n/a	n/a
	<i>Black or African-American</i>	1.08	0.83–1.41	0.57
	<i>Asian</i>	0.93	0.55–1.56	0.78
	<i>Other</i>	1.16	0.92–1.46	0.22
	<i>Missing</i>	1.19	0.82–1.72	0.37
Payer				
	<i>Private insurance</i>	1	n/a	n/a
	<i>Public insurance</i>	0.88	0.73–1.07	0.18
	<i>Other</i>	0.97	0.74–1.28	0.84
History of prematurity		0.62	0.41–0.95	0.03
Genetic syndrome		0.99	0.75–1.31	0.96
Non-cardiac structural anomaly		1.01	0.75–1.36	0.96
Cardiac operation prior to catheterization		2.32	1.67–3.22	<0.001
Pre-procedural medical care				
	<i>Mechanical ventilation</i>	0.92	0.70–1.20	0.53
	<i>Inotropic agents</i>	1.51	1.11–2.05	0.009
	<i>Systemic vasodilators</i>	1.81	1.29–2.56	0.001
	<i>Pulmonary vasodilators</i>	0.47	0.23–0.96	0.04
	<i>Hemodialysis</i>	17.2	5.4–54.9	<0.001
Intervention during procedure		0.24	0.20–0.29	<0.001

Abbreviations: CHD: congenital heart disease, CI: confidence interval

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