ELSEVIER

The Journal of Heart and Lung Transplantation

http://www.jhltonline.org

ORIGINAL CLINICAL SCIENCE

Center experience is associated with greater survival following donation after circulatory death heart transplantation

Brian E. Woolley, BS,[a] Yeahwa Hong, MD, PhD,[a,b] Umar Nasim, BS,[a] Nidhi Iyanna, MPH,[a] Ander Dorken-Gallastegi, MD,[b] Samantha N. Machinski, BA,[a] Gavin W. Hickey, MD,[c] Mary E. Keebler, MD,[c] Edward T. Horn, PharmD,[d] and David J. Kaczorowski, MD[a]

From the [a]Department of Cardiothoracic Surgery, University of Pittsburgh Medical Center, Pittsburgh, Pennsylvania; [b]Department of Surgery, University of Pittsburgh Medical Center, Pittsburgh, Pennsylvania; [c]Division of Cardiology, University of Pittsburgh Medical Center, Pittsburgh, Pennsylvania; and the [d]Department of Pharmacy and Therapeutics at the University of Pittsburgh Medical Center, Pittsburgh, Pennsylvania.

KEYWORDS:
heart transplantation;
donation after circulatory death;
transplant center volume;
heart utilization;
transplant outcomes

BACKGROUND: Higher center volume has been associated with improved outcomes in solid organ transplantation. However, the impact of center experience on donation after circulatory death (DCD) heart transplantation outcomes remains unclear. This study evaluates the association between cumulative DCD center experience and DCD post-transplant survival.

METHODS: The United Network for Organ Sharing registry was queried for adult recipients who underwent DCD heart transplantation from January 1, 2019 to December 31, 2023. Recipients were stratified by cumulative DCD center experience into low (≤10), intermediate (11-24), and high (≥25) transplant volume centers. The primary outcome was 1-year post-transplant survival. A restricted cubic spline (RCS) model was used to assess the volume-outcome relationship.

RESULTS: A total of 1,114 DCD heart transplant recipients across 59 centers were included. Low cumulative DCD volume was associated with lower 1-year DCD post-transplant survival compared to high-volume centers when controlling for confounders (89.0% vs 92.9%, $p = 0.025$), independent of donation after brain death (DBD) center volume and center-level DBD post-transplant survival. RCS showed decreasing 1-year post-transplant mortality with increasing DCD volume up to 20 DCD cases, beyond which survival gains plateaued. Normothermic regional perfusion was associated with similar survival compared to direct procurement and perfusion across all center volume categories.

CONCLUSIONS: Higher cumulative DCD center experience is associated with improved 1-year DCD post-transplant survival independent of DBD center volume or performance. Survival gains plateau after approximately 20 cumulative DCD cases. These findings highlight the importance of DCD-specific institutional experience and support the expansion of DCD heart transplantation to more centers while maintaining favorable outcomes.

J Heart Lung Transplant 2026;45:47–56

Corresponding author: David J. Kaczorowski, MD, Department of Cardiothoracic Surgery, University of Pittsburgh Medical Center, 200 Lothrop Street, Suite C700, Pittsburgh, PA 15213.

E-mail address: kaczorowskidj2@upmc.edu.

https://doi.org/10.1016/j.healun.2025.08.015

Background

Heart transplant continues to be the definitive treatment for select patients with end-stage heart failure.[1] However, the persistent organ shortage and increasing demand for donor hearts limit access and worsen outcomes for patients with end-stage heart failure.[2] Donation after circulatory death (DCD) refers to organ retrieval following irreversible cessation of circulation, in contrast to donation after brain death (DBD). In the United States, death is defined by the Uniform Determination of Death Act as the irreversible cessation of circulatory or brain function, though criteria vary internationally.[3] Historically, the first US heart transplant by Dr Norman Shumway in 1968 involved a donor with cardiac arrest, but modern DCD heart transplantation was first reported in the United States by Boucek et al, who described 3 pediatric cases in 2004-2007.[4,5] After a prolonged hiatus, clinical DCD heart transplantation was reintroduced in 2019 and is increasingly adopted to expand the donor pool. While short-term outcomes appear comparable to DBD, long-term graft performance remains uncertain.[6-9]

DCD heart transplantation presents unique challenges, including optimizing procurement techniques, managing warm ischemic time, and mitigating primary graft dysfunction.[10-12] There are 2 main techniques for DCD heart procurement: direct procurement and perfusion (DPP) and normothermic regional perfusion (NRP). In DPP, the heart is rapidly removed and perfused ex situ using an organ perfusion device. In NRP, systemic circulation is re-established in situ after exclusion of cerebral circulation, allowing functional assessment before explantation.[13] Limited data exist on whether procurement technique influences outcomes. Some reports suggest NRP may facilitate better graft function and early survival, but no definitive evidence establishes superiority over DPP.[14-16]

Higher transplant volume is consistently associated with better outcomes across solid organ transplants, highlighting the importance of institutional experience and expertise in improving transplant success.[17,18] In heart transplantation in particular, high-volume centers perform transplants in higher-risk patients but may achieve similar postoperative outcomes and improved long-term survival compared to low-volume centers.[19,20] There is no published literature assessing the impact of DCD center volume on outcomes of DCD heart transplantation, which is of particular relevance as the number of centers and total number of DCD heart transplants increases steadily year over year.[21] In this study, we evaluated the association between DCD center experience and recipient survival after DCD heart transplantation.

Methods

Data source

This study was conducted using deidentified donor and recipient data sourced from the United Network for Organ Sharing (UNOS) registry, a prospectively maintained national database that records all solid organ transplants performed within the United States. The study protocol received approval from the institutional review board of the University of Pittsburgh Medical Center (MOD18120143-003). Given the retrospective nature of the study, the requirement for informed consent was waived.

Study population and outcomes

The study cohort comprised adult recipients (age ≥18 years) who underwent heart transplantation from DCD donors between January 1, 2019, and December 31, 2023, with follow-up extending through December 31, 2024. Patients were excluded if they had received multivisceral or heterotopic transplants or had undergone retransplantation. Recipients were stratified by their center's cumulative DCD transplant experience during the study period into 3 categories: low (≤10 transplants), intermediate (11-24), and high (≥25). These thresholds were selected based on the distribution of DCD cases among centers to maintain adequate sample size and statistical power. We used cumulative rather than annual volume because DCD heart transplantation is relatively new, and cumulative experience may better reflect institutional learning curves and proficiency.

The primary outcome was survival at 1-year post-transplant. Secondary end-points included incidence of post-surgical complications, requirement for permanent pacemaker implantation, duration of hospitalization, and occurrence of acute rejection necessitating medical intervention. A subanalysis was conducted to evaluate the influence of DCD procurement techniques on survival across the different volume categories. For this, recipients were divided into 2 groups based on procurement method: DPP vs NRP. UNOS does not collect detailed data on procurement techniques; therefore, procurement method was inferred using the time interval between donor death pronouncement and donor cross-clamp. Hearts with an interval ≤30 minutes were categorized as DPP, while those with an interval >30 minutes were classified as NRP. This classification approach aligns with prior published methodology.[22]

Data analysis

Descriptive statistics were used to summarize baseline demographic and clinical variables, with categorical variables expressed as frequencies and percentages, and continuous variables presented as means with standard deviations or medians with interquartile ranges. Comparisons across center volume groups were performed using Pearson's chi-square test or Fisher's exact test for categorical variables and 1-way analysis of variance or Kruskal-Wallis tests for continuous variables, as appropriate. Hemodynamic variables were derived from the last assessment before transplantation (UNOS TRR form). Patients with missing values were included in descriptive analyses; the extent of missingness for each variable is detailed in Supplemental Table 1. Kaplan-Meier survival analysis, accompanied by the log-rank test, was employed to compare overall post-transplant survival.

To examine the relationship between center volume and 1-year post-transplant mortality, a restricted cubic spline model based on logistic regression was constructed. This model incorporated 5 knots, with a reference center volume of 1. A multivariable Cox proportional hazards regression model with robust standard errors clustered by transplant center to account for intracenter correlation was used to evaluate the impact of center volume on 1-year post-transplant mortality. Center volume was categorized into low-, intermediate-, and high-volume groups, and the model was adjusted for established risk factors of 1-year post-transplant mortality.[23] Estimated glomerular filtration rate (eGFR) was calculated using the 2021 chronic kidney disease epidemiology collaboration equation, assuming an eGFR of 0 for recipients receiving dialysis at transplant.[24] Predicted heart mass was calculated per international society of heart and lung transplantation-recommended formulas, and size mismatch was defined as a donor-to-recipient predicted heart mass ratio <0.86 per prior literature.[25] Annual center-level DBD transplant volume and post-transplant survival were included as covariates to adjust for overall institutional performance; centers were stratified into tertiles based on their 1-year DBD survival. Patients with missing covariates were excluded from the multivariable analysis. All statistical analyses were performed using Stata version 17 (StataCorp LP, College Station, TX), and significance was defined as a 2-sided $p < 0.05$.

Results

Baseline recipient, donor, and transplant characteristics

A total of 1,114 DCD heart transplant recipients were included in this study who received transplants across 59 centers (Figure 1A). There were 34 low- (57.6%), 11 intermediate- (18.6%), and 14 high-volume (23.7%) centers defined as having performed a total of ≤10, 11 to 24, and ≥25 DCD heart transplants, respectively. Of the recipients, 152 (13.6%) were transplanted at low-, 198 (17.8%) at intermediate-, and 764 (68.6%) at high-volume centers. The annual number of DCD heart transplants performed increased overall and within each center volume cohort during the study period (Figure 1B). In 2023, low-, intermediate-, and high-volume centers performed 100 (19.2%), 117 (22.5%), and 304 (58.3%) DCD transplants, respectively.

Heart transplant recipients at low-volume centers were, on average, of higher functional status and higher waitlist status and were more likely to be bridged to transplant with Impella (11.2% vs 4.5%, $p = 0.001$) compared to recipients at high-volume centers. Additionally, low-volume center recipients spent more time on waitlist (43.5 vs 25 days, $p = 0.009$) and had a shorter distance from donor hospital to

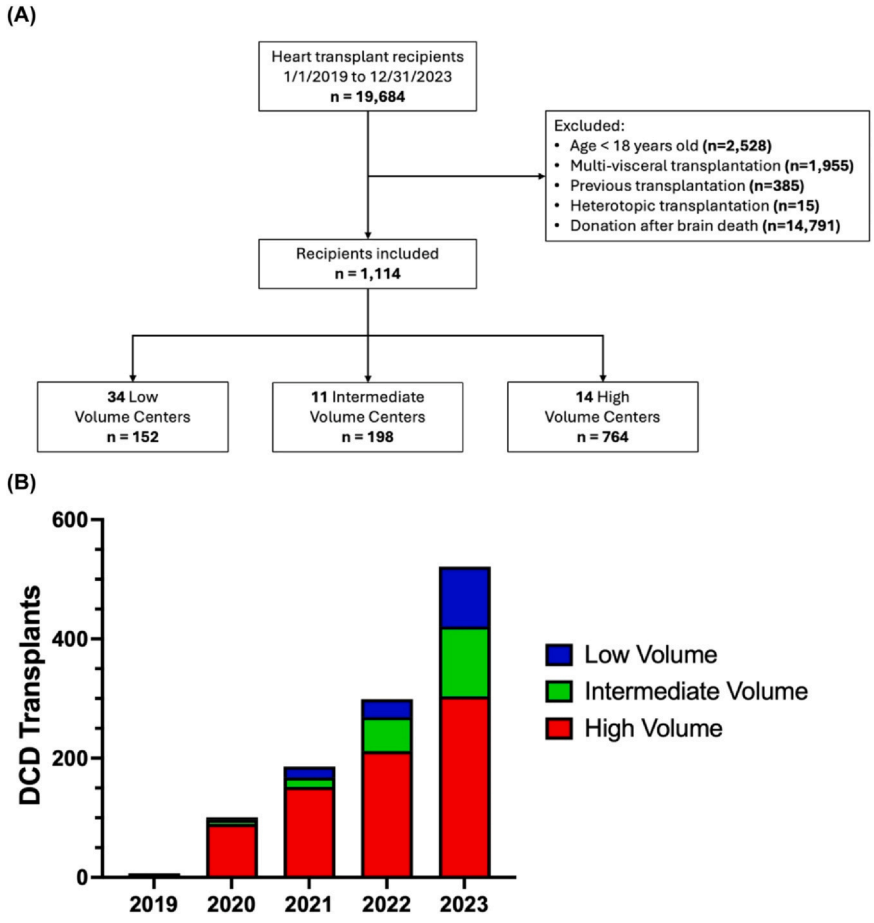

Figure 1 (A) Diagram of study inclusion criteria. (B) Total DCD transplants performed by year stratified by cumulative DCD center volume. Low volume: ≤10 DCD transplants, intermediate volume: 11 to 24 DCD transplants, high volume: ≥25 DCD transplants. DCD, donation after circulatory death.

transplant center (249.5 vs 364 nautical miles, $p < 0.001$) relative to high-volume centers (Table 1).

Intermediate-volume center recipients were of higher functional status, had a higher cardiac index (2.26 vs 2.12, $p = 0.004$), and were more likely to receive pretransplant mechanical ventilation (2% vs 0.3%, $p = 0.005$), intravenous inotropes (37.4% vs 29.5%, $p = 0.032$), waitlist transfusion (29.8% vs 8.4%, $p < 0.001$), be placed on ECMO before transplant (3.0% vs 1.0%, $p = 0.038$), and be bridged to transplant with Impella (9.1% vs 4.5%, $p = 0.010$) compared to high-volume centers. Furthermore, recipients at intermediate-volume centers spent more days on the waitlist (52 vs 25, $p < 0.001$), had shorter donor hospital to transplant center distance (247.5 vs 364 nautical miles, $p = 0.001$), and shorter ischemic time (4.7 vs 5.2 hours, $p = 0.015$) in relation to high-volume centers. Donor characteristics across the center volume groups were comparable (all $p > 0.05$; Table 1).

Effect of DCD center experience on post-transplant outcomes

In an unmatched comparison, recipients at high-volume centers had similar 1-year post-transplant survival as recipients at intermediate-volume centers (92.9% vs 94.3%, $p = 0.512$) and greater survival than those at low-volume centers (92.9% vs 89.0%, $p = 0.116$) although not significant (Fig. 2). Heart transplant recipients at high-volume centers had similar hospital lengths of stay and rates of post-transplant dialysis, stroke, and acute rejection requiring medical therapy compared to recipients in both the intermediate and low center volume cohorts (all $p > 0.05$, Table 2).

Table 1 Baseline Recipient, Donor, and Transplant Characteristics Stratified by Donation After Circulatory Death (DCD) Transplant Center Volume

Parameter	Low volume (N = 152)	Intermediate volume (N = 198)	High volume (N = 764)	*p*-value[a]
Recipient characteristics				
Recipient age (years)	57 (47-64)	56 (42-64)	57 (46-64)	0.634
Female sex	28 (18.4%)	37 (18.7%)	160 (20.9%)	0.657
Body mass index (kg/m^2)	28.11 (4.72)	28.49 (4.78)	28.53 (4.98)	0.624
Recipient race				0.357
White	101 (66.9%)	132 (66.7%)	522 (68.5%)	
Black	27 (17.9%)	37 (18.7%)	156 (20.5%)	
Hispanic	20 (13.2%)	21 (10.6%)	66 (8.7%)	
Asian	1 (0.7%)	7 (3.5%)	14 (1.8%)	
Other	2 (1.3%)	1 (0.5%)	4 (0.5%)	
Blood type				0.025
A	61 (40.1%)	85 (42.9%)	247 (32.3%)	
AB	1 (0.7%)	7 (3.5%)	25 (3.3%)	
B	20 (13.2%)	16 (8.1%)	92 (12.0%)	
O	70 (46.1%)	90 (45.5%)	400 (52.4%)	
Education level				0.061
High school	65 (44.2%)	82 (43.2%)	272 (36.1%)	
College	67 (45.6%)	97 (51.1%)	397 (52.7%)	
Graduate degree	15 (10.2%)	11 (5.8%)	84 (11.2%)	
Functional status				0.004
Independent	16 (11.8%)	22 (13.4%)	48 (6.3%)	
Requires assistance	56 (41.2%)	68 (41.5%)	386 (50.6%)	
Hospitalized	64 (47.1%)	74 (45.1%)	329 (43.1%)	
Heart failure etiology				0.351
Nonischemic	75 (49.3%)	107 (54.0%)	403 (52.7%)	
Ischemic	46 (30.3%)	57 (28.8%)	211 (27.6%)	
Congenital	3 (2.0%)	9 (4.5%)	25 (3.3%)	
Restrictive	8 (5.3%)	8 (4.0%)	34 (4.5%)	
Valvular	3 (2.0%)	7 (3.5%)	12 (1.6%)	
Hypertrophic	10 (6.6%)	5 (2.5%)	32 (4.2%)	
Missing	7 (4.6%)	5 (2.5%)	47 (6.2%)	
Prior cardiac surgery	53 (34.9%)	89 (44.9%)	339 (44.4%)	0.083
Intensive care unit state at time of transplantation	62 (40.8%)	68 (34.3%)	261 (34.2%)	0.286
Pretransplant dialysis	2 (1.3%)	3 (1.5%)	9 (1.2%)	0.928
Pretransplant mechanical ventilation	1 (0.7%)	4 (2.0%)	2 (0.3%)	0.020
Pretransplant infection	10 (6.6%)	16 (8.1%)	34 (4.5%)	0.106
Intravenous inotropes	55 (36.2%)	74 (37.4%)	225 (29.5%)	0.047

(*continued on next page*)

Table 1 (*Continued*)

Parameter	Low volume (N = 152)	Intermediate volume (N = 198)	High volume (N = 764)	*p*-value[a]
Waitlist for blood transfusion	17 (11.2%)	59 (29.8%)	64 (8.4%)	< 0.001
Cerebrovascular accident	12 (7.9%)	17 (8.6%)	54 (7.1%)	0.750
Diabetes mellitus	41 (27.0%)	60 (30.3%)	235 (30.8%)	0.649
Positive CMV serology	72 (47.4%)	101 (51.0%)	399 (52.2%)	0.547
Total bilirubin (mg/dl)	0.7 (0.4-1)	0.7 (0.5-1.1)	0.7 (0.48-1)	0.725
Serum creatinine (mg/dl)	1.13 (0.96-1.35)	1.09 (0.92-1.30)	1.14 (0.93-1.39)	0.261
IABP	28 (18.4%)	31 (15.7%)	109 (14.3%)	0.413
ECMO	3 (2.0%)	6 (3.0%)	8 (1.0%)	0.090
Impella	17 (11.2%)	18 (9.1%)	34 (4.5%)	0.001
Impella CP	0 (0%)	1 (6%)	5 (15%)	
Impella 5.0	5 (29%)	6 (33%)	4 (12%)	
Impella 5.5	12 (71%)	11 (61%)	25 (74%)	
Durable LVAD	29 (19.1%)	52 (26.3%)	195 (25.5%)	0.211
HeartMate 3	22 (14.5%)	38 (19.2%)	156 (20.4%)	
HeartMate 2	1 (0.7%)	4 (2.0%)	17 (2.2%)	
HeartWare HVAD	6 (3.9%)	10 (5.1%)	22 (2.9%)	
Cardiac output[b] (liter/min)	4.50 (1.46)	4.69 (1.44)	4.42 (1.26)	0.043
Cardiac index[b] (liter/min/m^2)	2.08 (0.66)	2.26 (0.72)	2.12 (0.56)	0.008
Pulmonary artery pressure[b] (mm Hg)	26.67 (9.71)	26.92 (10.11)	26.54 (10.22)	0.896
Pulmonary capillary wedge pressure[b] (mm Hg)	17.22 (8.39)	17.69 (9.18)	17.36 (8.79)	0.882
Pulmonary vascular resistance[b] (Wood units)	2.45 (1.54)	2.25 (1.44)	2.35 (1.58)	0.524
Transpulmonary gradient[b] (mm Hg)	9.72 (4.34)	9.48 (4.45)	9.46 (5.19)	0.850
eGFR[c] (ml/min/1.73 m^2)	73.79 (25.27)	77.40 (26.80)	73.40 (25.21)	0.142
Donor characteristics				
Donor age	30 (25-34)	30 (23-36)	31 (24-38)	0.160
Female sex	27 (17.8%)	36 (18.2%)	102 (13.4%)	0.127
Body mass index	28.26 (6.54)	27.65 (6.62)	27.61 (6.24)	0.505
Donor race				0.405
White	127 (83.6%)	154 (77.8%)	576 (75.4%)	
Black	14 (9.2%)	15 (7.6%)	76 (9.9%)	
Hispanic	10 (6.6%)	24 (12.1%)	91 (11.9%)	
Asian	0 (0.0%)	3 (1.5%)	10 (1.3%)	
Other	1 (0.7%)	2 (1.0%)	11 (1.4%)	
Donor blood type				0.109
A	47 (30.9%)	75 (37.9%)	216 (28.3%)	
AB	0 (0.0%)	2 (1.0%)	2 (0.3%)	
B	13 (8.6%)	15 (7.6%)	63 (8.2%)	
O	92 (60.5%)	106 (53.5%)	483 (63.2%)	
Donor mechanism of death				0.735
Trauma	74 (48.7%)	89 (44.9%)	315 (41.2%)	
Cardiovascular	12 (7.9%)	18 (9.1%)	68 (8.9%)	
Drug overdose	33 (21.7%)	43 (21.7%)	180 (23.6%)	
Other	33 (21.7%)	48 (24.2%)	201 (26.3%)	
Donor diabetes mellitus	3 (2.0%)	2 (1.0%)	26 (3.4%)	0.155
Donor hepatitis C	10 (6.6%)	14 (7.1%)	76 (9.9%)	0.243
Positive CMV serology	78 (52.3%)	118 (59.9%)	415 (55.2%)	0.339
Hypertension	17 (11.3%)	14 (7.1%)	108 (14.2%)	0.026
Low EF (< 50%)	0 (0.0%)	1 (0.5%)	11 (1.4%)	0.317
Total bilirubin (mg/dl)	0.70 (0.6-0.9)	0.74 (0.6-1.0)	0.76 (0.6-1.0)	0.505
Serum creatinine (mg/dl)	0.6 (0.4-0.9)	0.5 (0.4-0.9)	0.6 (0.4-0.9)	0.705
Transplant characteristics				
Sex matched	133 (87.5%)	167 (84.3%)	640 (83.8%)	0.512
Race matched	94 (61.8%)	109 (55.1%)	437 (57.2%)	0.431
HLA matched	16 (10.5%)	18 (9.1%)	86 (11.3%)	0.678
ABO matched	129 (84.9%)	178 (89.9%)	660 (86.4%)	0.322
CMV status matched	86 (57.7%)	97 (49.2%)	378 (50.3%)	0.213
Size matched[d]	12 (7.9%)	26 (13.1%)	96 (12.6%)	0.236

(*continued on next page*)

Table 1 (*Continued*)

Parameter	Low volume (N = 152)	Intermediate volume (N = 198)	High volume (N = 764)	*p*-value[a]
Waitlist time (days)	44 (11-199.5)	52 (12-283)	25 (8-137)	< 0.001
Distance-recipient distance (nautical miles)	250 (94-467)	248 (60-527)	364 (139-573)	< 0.001
Total graft ischemic time (hours)	5.2 (2.6-6.3)	4.7 (2.7-6.4)	5.2 (3.7-6.6)	0.031
Direct procurement and perfusion	101 (66.4%)	113 (57.1%)	455 (59.6%)	0.182
Normothermic regional perfusion	51 (33.6%)	85 (42.9%)	309 (40.4%)	0.182
Machine perfusion	103 (67.8%)	126 (63.6%)	493 (64.5%)	0.695
Waitlist status at transplantation				0.001
1	5 (3.3%)	7 (3.5%)	16 (2.1%)	
2	78 (51.3%)	68 (34.3%)	264 (34.6%)	
3	21 (13.8%)	33 (16.7%)	138 (18.1%)	
4	27 (17.8%)	71 (35.9%)	221 (28.9%)	
5	0 (0.0%)	0 (0.0%)	3 (0.4%)	
6	21 (13.8%)	19 (9.6%)	122 (16.0%)	

Abbreviations: CMV, cytomegalovirus; ECMO, extracorporeal membrane oxygenation; EF, ejection fraction; eGFR, estimated glomerular filtration rate; HLA, human leukocyte antigen; HVAD, heartware ventricular assist device; IABP, intra-aortic balloon pump; LVAD, left ventricular assist device; PVR, pulmonary vascular resistance; TPG, transpulmonary gradient; TRR PCW, transplant recipient registry pulmonary capillary wedge pressure.

Missing data for baseline characteristics are summarized in Supplemental Table 1. High volume: ≥25 transplants, intermediate volume: 11-24 DCD transplants, low volume: ≤10 transplants.

Missing data: PVR (8.6%), TPG (7.8%), TRR PCW (5.6%). All other variables < 5%.

[a]*p*-values represent comparisons across low-, intermediate-, and high-volume centers. Continuous variables were compared using ANOVA or Kruskal-Wallis tests, and categorical variables using chi-square or Fisher's exact tests as appropriate.

[b]Hemodynamic variables were obtained from the last assessment before transplantation (UNOS TRR form).

[c]eGFR calculated using the 2021 CKD-EPI equation, assuming an eGFR of 0 for recipients on dialysis at transplant.

[d]Size mismatch defined as donor-recipient predicted heart mass ratio < 0.86. Calculated per ISHLT-recommended formulas.

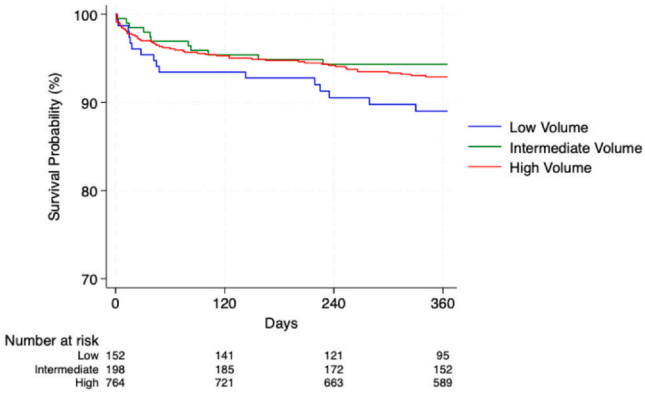

Figure 2 One-year survival following donation after circulatory death heart (DCD) transplantation by cumulative DCD center volume.

After multivariable adjustment for established risk factors and clustering by transplant center, recipients transplanted at low-volume centers had significantly higher risk of 1-year mortality compared to those at high-volume centers (hazard ratio 2.19; 95% confidence interval, 1.27-3.79; $p = 0.005$). Intermediate-volume centers had similar outcomes to high-volume centers (hazard ratio 1.03; 95% confidence interval, 0.57-1.86; $p = 0.919$). Neither annual DBD center volume or center-level DBD 1-year post-transplant survival predicted DCD post-transplant outcomes (Table 3). Furthermore, stratification of transplant centers into tertiles by cumulative DBD center volume demonstrated similar DCD post-transplant survival at low, intermediate, and high DBD volume centers (92.5% vs 93.0% vs 92.4%, $p = 0.967$, Supplemental Figure 2).

Restricted cubic spline based on logistic regression was performed to flexibly model the association between cumulative DCD center volume and odds of 1-year post-transplant mortality.[26] The spline model demonstrated decreasing odds of 1-year mortality as DCD center volume increases up to approximately 20 cases compared to the reference center volume of 1 (Figure 3).

Table 2 Post-transplant Outcomes Stratified by Cumulative Donation After Circulatory Death Center Volume

Complication	Low volume (N = 152)	Intermediate volume (N = 198)	High volume (N = 764)	*p*-value[a]
Dialysis	32 (21.1%)	41 (20.7%)	125 (16.4%)	0.190
Stroke	4 (2.6%)	12 (6.1%)	33 (4.3%)	0.300
Permanent pacemaker implantation	5 (3.3%)	0 (0.0%)	9 (1.2%)	0.023
Length of stay (days)	16 (13-27)	16 (12-25)	16 (12-24)	0.370
Treated acute rejection	12 (7.9%)	13 (6.6%)	73 (9.6%)	0.380

[a]*p*-values represent comparisons across low-, intermediate-, and high-volume centers. Continuous variables were compared using ANOVA or Kruskal-Wallis tests, and categorical variables using chi-square or Fisher's exact tests as appropriate.

Table 3 Adjusted Cox Proportional Hazards Model for 1-year Post-transplant Mortality (n = 1,112)

Variable	Hazard ratio	95% Confidence interval		p-value
Cumulative DCD center volume				
High (≥25)	Ref	Ref	Ref	
Intermediate (11-24)	1.03	0.57	1.86	0.919
Low (≤10)	2.19	1.27	3.79	0.005
Recipient age, increasing, per year	1.02	0.99	1.05	0.153
Diabetes mellitus	1.32	0.89	1.95	0.161
Durable LVAD	1.83	1.21	2.75	0.004
Pretransplant mechanical ventilation	3.90	0.71	21.32	0.116
Total bilirubin, increasing, per mg/dl	2.02	1.20	3.41	0.009
eGFR, increasing, per ml/min/1.73 m^2[a]	0.99	0.98	1.00	0.009
Donor age, increasing, per year	0.99	0.96	1.01	0.316
Donor female sex	0.77	0.38	1.56	0.476
Donor-recipient size mismatch[b]	1.44	0.95	2.19	0.089
DBD annual center volume, increasing, per 10 transplants	1.02	0.99	1.04	0.169
DBD center-level 1-year post-transplant survival[c]				
High	Ref	Ref	Ref	
Intermediate	0.79	0.27	2.36	0.678
Low	0.84	0.61	1.17	0.303

Abbreviations: DBD, donation after brain death; DCD, donation after circulatory death; eGFR, estimated glomerular filtration rate; LVAD, left ventricular assist device.

Robust standard errors were calculated using clustering by transplant center to account for within-center correlation.

Missing data: 2 patients were excluded due to missing covariates.

[a]eGFR calculated using the 2021 CKD-EPI equation, assuming an eGFR of 0 for recipients on dialysis at transplant.

[b]Size mismatch defined as donor-recipient predicted heart mass ratio < 0.86. Calculated per ISHLT-recommended formulas.

[c]DBD center-level 1-year post-transplant survival categories were derived by stratifying all centers performing DBD transplants during the study period into tertiles based on 1-year survival probability among DBD heart transplant recipients.

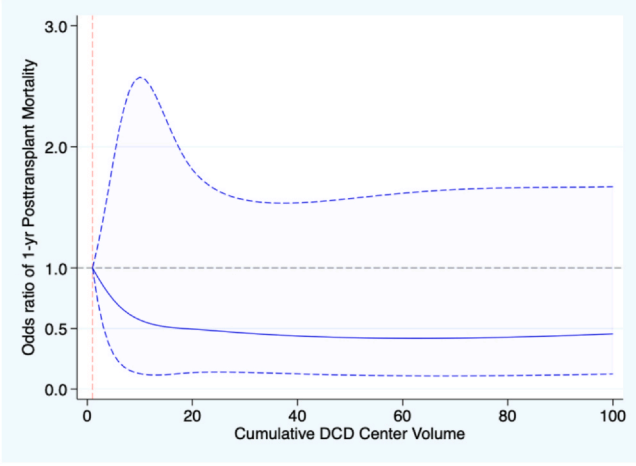

Figure 3 Odds of 1-year post-transplant mortality by cumulative DCD center volume. The shaded region indicates the 95% confidence interval for the spline estimate. DCD, donation after circulatory death.

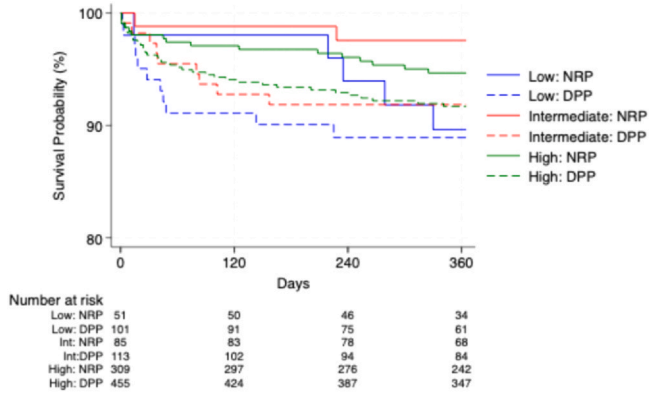

Figure 4 One-year survival following donation after circulatory death heart (DCD) transplantation stratified by total DCD center volume and procurement type. DPP, direct procurement and perfusion; NRP, normothermic regional perfusion.

Effect of center experience and procurement method on post-transplant outcomes

Of the DCD transplants performed during the study period, 445 donor hearts (40.0%) underwent NRP, and the remaining 669 donor hearts (60.1%) underwent DPP. NRP was more commonly employed at intermediate- and high-volume centers, where 85 (42.9%) and 309 (40.5%) donor hearts underwent NRP, respectively, compared to low-volume centers in which 51 (33.6%) underwent NRP. NRP yielded statistically similar, although, numerically higher 1-year post-transplant survival within low (89.6% vs 88.9%, p = 0.737), intermediate (97.6% vs 91.9%, p = 0.084), and high (94.7% vs 91.7%, p = 0.110) volume centers (Figure 4).

Discussion

This study investigated the association between DCD center volume and post-transplant outcomes utilizing a national registry database. Our results demonstrate that (1) higher cumulative DCD center volume is associated with greater 1-year post-transplant survival in DCD recipients, (2) survival benefits of increasing DCD center volume plateau at approximately 20 cumulative DCD transplants, and (3) DCD center experience is independently associated with improved DCD performance independent of DBD center volume and performance.

Interest in DCD heart transplantation in the United States was reignited in 2019, with the aim of addressing the critical shortage of donor hearts by increasing the number of donor hearts available for transplantation. Since then, the proportion of heart transplants involving DCD allografts has increased significantly from 2% in December 2019 to 11% in 2023.[9] Similarly, the number of centers that perform DCD transplants has grown dramatically from only 3 centers in 2019 to 59 centers as of the end of 2023.[27]

The center volume-outcome relationship has been well-studied in cardiac transplantation, with studies consistently reporting that high-volume centers have shorter waitlist times, and improved waitlist and post-transplant outcomes compared to low-volume centers.[19,28-32] However, these studies have exclusively analyzed patients before the introduction of DCD heart transplantation in the United States. A single study by Bakhtiyar et al addresses the impact of center volume on outcomes of DCD heart transplantation and reports comparable post-transplant survival following DBD and DCD with NRP or DPP procurement at 1- and 3-year follow-up between high- and low-volume centers.[9] A limitation of their analysis is that center volume is stratified by total annual heart transplantation volume, which includes DBD and DCD recipients, and therefore does not directly capture a transplant centers' DCD experience.

In this study, we stratified transplant centers by cumulative DCD center volume during the study period and observed that higher DCD center experience was associated with greater DCD post-transplant survival. Specifically, high-volume (≥25 DCD transplants) centers had greater 1-year post-transplant survival compared to low-volume (≤10 DCD transplants) centers when adjusting for confounders. Additionally, in a multivariable analysis, annual DBD center volume and center-level DBD post-transplant survival were not significant predictors of DCD outcomes. The contrast between our results and the findings of Bakhtiyar et al highlights the significant impact that DCD-specific experience has on post-transplant outcomes, demonstrating the unique challenges of DCD heart transplantation. This represents an opportunity for the development and dissemination of DCD-specific guidelines to bridge the knowledge gap between experienced DCD transplant centers and less experienced centers.

High-volume centers had similar post-transplant survival compared to intermediate-volume (11-24 DCD transplants) centers. Restricted cubic spline analysis demonstrated that increasing DCD center volume was associated with survival benefit up to approximately 20 total DCD transplants, beyond which additional gains plateaued. This supports the notion of safe expansion of DCD heart transplantation to a growing number of transplant centers without sacrificing outcomes for recipients at these centers. It also indicates that transplant centers outside of the largest DCD volume centers should confidently consider DCD hearts for their candidates.

Our findings provide evidence of the benefit of institutional experience with DCD in overcoming the additional challenges compared to traditional DBD heart transplantation. The primary challenge is the exposure of DCD hearts to warm ischemia. DPP and NRP are 2 primary procurement methods used in DCD heart transplantation to mitigate the risks associated with warm ischemic time.[7,11,33] Both approaches seek to minimize myocardial damage and allow for functional assessment of the heart, and have been reported to extend the acceptable warm ischemic time and enhance overall organ yield.[34-37] Studies of the early experience with DCD heart transplant in the United States using the UNOS registry indicate high variability in procurement strategy by geographic region and transplant center.[14,15] Several studies have compared outcomes between DPP and NRP and consistently report similar or slightly improved post-transplant survival and graft function associated with NRP compared to DPP.[14,15] Many center-related factors influence the choice of procurement method, including available resources, regional ethical preferences, desired length of functional assessment, and median distance traveled, and interestingly, while many centers use both DPP and NRP, greater than 80% of centers demonstrate a clear preference for 1 strategy.[15,38,39] Our study shows that NRP results in similar 1-year post-transplant survival across center volume categories compared to DPP, although notably numerically greater survival particularly at intermediate- and high-volume centers, indicating that NRP may be associated with a survival benefit compared to DPP when performed at experienced centers with greater optimization of procurement methods. This is likely due to the added technical complexity of re-establishing blood flow to the heart in situ while ensuring no restoration of brain perfusion in NRP, and points toward the potential role of NRP in improved outcomes of DCD transplant.[40-42]

Limitations

This study has several limitations. Its retrospective, non-randomized design introduces potential biases, including selection, misclassification, recall, and documentation bias. As with other multicenter databases, the UNOS registry is subject to inaccuracies and missing data and lacks detailed information on key transplant variables, such as donor management, procurement techniques, surgeon preferences, and postoperative care, which may confound the volume-outcome relationship. Additionally, critical outcomes such as the need for post-transplant mechanical circulatory support are not reported, nor are details of perfusion device type or perfusate composition. Procurement method (NRP

vs DPP) was inferred using time intervals, which may introduce misclassification bias. Selection bias is also possible, as centers performing a high volume of DCD transplants likely represent programs with greater resources, specialized expertise, and institutional commitment to DCD adoption, which may limit generalizability. Reverse causality cannot be excluded; centers experiencing poor early outcomes may have curtailed additional DCD activity, potentially influencing the observed volume-outcome relationship. Finally, although we adjusted for center-level DBD performance and applied clustering by center, residual confounding from unmeasured factors such as surgeon experience, institutional protocols, and donor management practices remains possible. The study is also limited to adult recipients of isolated heart transplants with a 1-year follow-up, restricting applicability to pediatric patients, multiorgan transplants, and longer-term outcomes.

Conclusion

This study demonstrates that higher cumulative DCD center experience is associated with improved survival following DCD heart transplantation independent of DBD volume and performance, with the greatest benefit seen in centers performing at least 20 DCD heart transplants. The survival advantage of higher DCD volume centers is likely attributable to institutional experience in managing the unique challenges of DCD heart transplantation, including procurement techniques, perioperative management, and long-term post-transplant care. Notably, the lack of a significant survival difference between intermediate- and high-volume centers suggests that safe expansion of DCD transplantation to more centers is feasible. Additionally, NRP was associated with similar survival across all center volume categories compared to DPP. As the utilization of DCD heart transplantation continues to grow, efforts to standardize best practices and disseminate expertise from high-volume centers will be critical in ensuring favorable outcomes across transplant centers.

CRediT authorship contribution statement

Brian E. Woolley: Concept/design, Data analysis/interpretation, Drafting article, Critical revision of article, Approval of article, Statistics. **Yeahwa Hong:** Concept/design, Data analysis/interpretation, Drafting article, Critical revision of article, Approval of article. **Nidhi Iyanna:** Drafting article, Critical revision of article, Approval of article. **Umar Nasim:** Drafting article, Critical revision of article, Approval of article, Statistics. **Ander Dorken-Gallastegi:** Critical revision of article, Approval of article. **Samantha N. Machinski:** Critical revision of article, Approval of article. **Gavin W. Hickey:** Critical revision of article, Approval of article. **Mary E. Keebler:** Critical revision of article, Approval of article. **Edward T. Horn:** Critical revision of article, Approval of article. **David J. Kaczorowski:** Concept/design, Data analysis/interpretation, Drafting article, Critical revision of article, Approval of article.

Disclaimer

The data reported here have been supplied by the UNOS as the contractor for the Organ Procurement and Transplantation Network. The interpretation and reporting of these data are the responsibility of the author(s) and in no way should be seen as an official policy of or interpretation by the OPTN or the US Government.

Disclosure statement

Dr David Kaczorowski received consultant and speaking fees from Medtronic and Abiomed, as well as research support from Abbott, TransMedics, and XVIVO. There are no direct conflicts of interest as it relates to this manuscript. The other authors of this manuscript have no conflicts of interest to disclose.

Acknowledgments: None.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.healun.2025.08.015.

References

1. Heidenreich PA, Bozkurt B, Aguilar D, et al. 2022 AHA/ACC/HFSA guideline for the management of heart failure: a report of the American College of Cardiology/American Heart Association joint committee on clinical practice guidelines. J Am Coll Cardiol 2022;79:e263-421. https://doi.org/10.1016/j.jacc.2021.12.012.
2. Miller L, Birks E, Guglin M, Lamba H, Frazier OH. Use of ventricular assist devices and heart transplantation for advanced heart failure. Circ Res 2019;124:1658-78. https://doi.org/10.1161/CIRCRESAHA.119.313574.
3. Bernat JL, Khush KK, Shemie SD, et al. Knowledge gaps in heart and lung donation after the circulatory determination of death: Report of a workshop of the National Heart, Lung, and Blood Institute. J Heart Lung Transplant 2024;43:1021-9. https://doi.org/10.1016/j.healun.2024.02.1455.
4. Baumgartner WA, Reitz BA, Gott VL, Shumway SJ. Norman E. Shumway, MD, PhD: visionary, innovator, humorist. J Thorac Cardiovasc Surg 2009;137:269-77. https://doi.org/10.1016/j.jtcvs.2008.11.008.
5. Boucek MM, Mashburn C, Dunn SM, et al. Pediatric heart transplantation after declaration of cardiocirculatory death. N Engl J Med 2008;359:709-14. https://doi.org/10.1056/NEJMoa0800660.
6. Scheuer SE, Jansz PC, Macdonald PS. Heart transplantation following donation after circulatory death: expanding the donor pool. J Heart Lung Transplant 2021;40:882-9. https://doi.org/10.1016/j.healun.2021.03.011.
7. Trela KC, Salerno CT, Chuba E, Dhawan R. Donation after circulatory death heart transplantation: a narrative review. J Cardiothorac Vasc Anesth 2024;38:2047-58. https://doi.org/10.1053/j.jvca.2024.03.045.
8. Siddiqi HK, Trahanas J, Xu M, et al. Outcomes of heart transplant donation after circulatory death. J Am Coll Cardiol 2023;82:1512-20. https://doi.org/10.1016/j.jacc.2023.08.006.

9. Bakhtiyar SS, Sakowitz S, Mallick S, Curry J, Benharash P. Heart transplantation after donation after circulatory death: early United States experience. Ann Thorac Surg 2024;118:484-93. https://doi.org/10.1016/j.athoracsur.2024.05.013.
10. Joshi Y, Scheuer S, Chew H, et al. Heart transplantation from DCD donors in Australia: lessons learned from the first 74 cases. Transplantation 2023;107:361-71. https://doi.org/10.1097/TP.0000000000004294.
11. Ayer A, Schroder JN, Casalinova S, et al. The future of heart procurement with donation after circulatory death: current practice and opportunities for advancement. J Heart Lung Transplant 2022;41:1385-90. https://doi.org/10.1016/j.healun.2022.06.016.
12. Niederberger P, Farine E, Raillard M, et al. Heart transplantation with donation after circulatory death. Circ Heart Fail 2019;12:e005517. https://doi.org/10.1161/CIRCHEARTFAILURE.118.005517.
13. Thomas J, Chen Q, Roach A, et al. Donation after circulatory death heart procurement strategy impacts utilization and outcomes of concurrently procured abdominal organs. J Heart Lung Transplant 2023;42:993-1001. https://doi.org/10.1016/j.healun.2023.02.1497.
14. Ran G, Wall AE, Narang N, et al. Post-transplant survival after normothermic regional perfusion versus direct procurement and perfusion in donation after circulatory determination of death in heart transplantation. J Heart Lung Transplant 2024;43:954-62. https://doi.org/10.1016/j.healun.2024.02.1456.
15. Benkert AR, Keenan JE, Schroder JN, et al. Early U.S. heart transplant experience with normothermic regional perfusion following donation after circulatory death. JACC Heart Fail 2024;12:2073-83. https://doi.org/10.1016/j.jchf.2024.06.007.
16. Pinney SP, Costanzo MR. Donation after circulatory death: shifting the paradigm in heart transplantation. J Am Coll Cardiol 2023;82:1521-3.
17. Axelrod DA, Guidinger MK, McCullough KP, Leichtman AB, Punch JD, Merion RM. Association of center volume with outcome after liver and kidney transplantation. Am J Transplant 2004;4:920-7. https://doi.org/10.1111/j.1600-6143.2004.00462.x.
18. Alqahtani SA, Stepanova M, Kabbara KW, Younossi I, Mishra A, Younossi Z. Liver transplant center size and the impact on clinical outcomes and resource utilization. Transplantation 2022;106:988-96. https://doi.org/10.1097/TP.0000000000003915.
19. Russo MJ, Iribarne A, Easterwood R, et al. Post-heart transplant survival is inferior at low-volume centers across all risk strata. Circulation 2010;122:S85-91. https://doi.org/10.1161/CIRCULATIONAHA.109.926659.
20. Sharaf OM, Bilgili A, Brennan Z, et al. Analysis of UNOS: pediatric heart transplantation over 36 years and contemporary volume-outcome relationship. Ann Thorac Surg 2024;118:1288-98. https://doi.org/10.1016/j.athoracsur.2024.05.003.
21. Chen Q, Emerson D, Megna D, et al. Heart transplantation using donation after circulatory death in the United States. J Thorac Cardiovasc Surg 2023;165:1849-1860 e6. https://doi.org/10.1016/j.jtcvs.2022.05.005.
22. Hong Y, Hess NR, Dorken-Gallastegi A, et al. Association of agonal phase duration with heart utilization and post-transplant outcomes in donation after circulatory death heart transplantation. J Heart Lung Transplant 2025;44:736-47. https://doi.org/10.1016/j.healun.2024.11.011.
23. Lazenby KA, Tolmie SB, Barrett K, et al. Development of a risk score predicting survival after adult heart transplantation in the United States. J Heart Lung Transplant 2025. https://doi.org/10.1016/j.healun.2025.07.004.
24. Inker LA, Eneanya ND, Coresh J, et al. New creatinine- and cystatin C-based equations to estimate GFR without race. N Engl J Med 2021;385:1737-49. https://doi.org/10.1056/NEJMoa2102953.
25. Kransdorf EP, Kittleson MM, Benck LR, et al. Predicted heart mass is the optimal metric for size match in heart transplantation. J Heart Lung Transplant 2019;38:156-65. https://doi.org/10.1016/j.healun.2018.09.017.
26. Kilic A, Weiss ES, George TJ, et al. What predicts long-term survival after heart transplantation? An analysis of 9,400 ten-year survivors. Ann Thorac Surg 2012;93:699-704. https://doi.org/10.1016/j.athoracsur.2011.09.037.
27. Kwon JH, Ghannam AD, Shorbaji K, et al. Early outcomes of heart transplantation using donation after circulatory death donors in the United States. Circ Heart Fail 2022;15:e009844. https://doi.org/10.1161/CIRCHEARTFAILURE.122.009844.
28. Shuhaiber JH, Moore J, Dyke DB. The effect of transplant center volume on survival after heart transplantation: a multicenter study. J Thorac Cardiovasc Surg 2010;139:1064-9. https://doi.org/10.1016/j.jtcvs.2009.11.040.
29. Weiss ES, Meguid RA, Patel ND, et al. Increased mortality at low-volume orthotopic heart transplantation centers: should current standards change? Ann Thorac Surg 2008;86:1250-9. https://doi.org/10.1016/j.athoracsur.2008.06.071.
30. Pettit SJ, Jhund PS, Hawkins NM, et al. How small is too small? A systematic review of center volume and outcome after cardiac transplantation. Circ Cardiovasc Qual Outcomes 2012;5:783-90. https://doi.org/10.1161/CIRCOUTCOMES.112.966630.
31. Garatti A, Daprati A, Cottini M, et al. Cardiac surgery in patients with liver cirrhosis (CASTER) study: early and long-term outcomes. Ann Thorac Surg 2021;111:1242-51. https://doi.org/10.1016/j.athoracsur.2020.06.110.
32. Critsinelis A, Karamchandani MM, Hironaka CE, et al. Heart transplant waitlist outcomes and wait time by center volume in the pre-2018 allocation change era. ASAIO J 2023;69:863-70. https://doi.org/10.1097/MAT.0000000000001966.
33. Arnold M, Do P, Davidson SM, et al. Metabolic considerations in direct procurement and perfusion protocols with dcd heart transplantation. Int J Mol Sci 2024;25:4153. https://doi.org/10.3390/ijms25084153.
34. Smith DE, Kon ZN, Carillo JA, et al. Early experience with donation after circulatory death heart transplantation using normothermic regional perfusion in the United States. J Thorac Cardiovasc Surg 2022;164:557-568 e1. https://doi.org/10.1016/j.jtcvs.2021.07.059.
35. Hoffman JRH, McMaster WG, Rali AS, et al. Early US experience with cardiac donation after circulatory death (DCD) using normothermic regional perfusion. J Heart Lung Transplant 2021;40:1408-18. https://doi.org/10.1016/j.healun.2021.06.022.
36. Feizpour CA, Gauntt K, Patel MS, et al. The impact of machine perfusion of the heart on warm ischemia time and organ yield in donation after circulatory death. Am J Transplant 2022;22:1451-8. https://doi.org/10.1111/ajt.16952.
37. Saemann L, Georgevici AI, Hoorn F, et al. Improving diastolic and microvascular function in heart transplantation with donation after circulatory death. Int J Mol Sci 2023;24. https://doi.org/10.3390/ijms241411562.
38. Gouchoe DA, Satija D, Cui EY, et al. Rise of the machines: normothermic regional perfusion use in heart transplantation in the United States. J Thorac Cardiovasc Surg 2024:268-76. https://doi.org/10.1016/j.jtcvs.2024.12.001.
39. Bakhtiyar SS, Maksimuk TE, Gutowski J, et al. Association of procurement technique with organ yield and cost following donation after circulatory death. Am J Transplant 2024;24:1803-15. https://doi.org/10.1016/j.ajt.2024.03.027.
40. Brogi E, Circelli A, Gamberini E, et al. Normothermic regional perfusion for controlled donation after circulatory death: a technical complication during normothermic regional perfusion. ASAIO J 2020;66:e19-21. https://doi.org/10.1097/MAT.0000000000000963.
41. Parent B, Moazami N, Wall S, et al. Ethical and logistical concerns for establishing NRP-cDCD heart transplantation in the United States. Am J Transplant 2020;20:1508-12. https://doi.org/10.1111/ajt.15772.
42. Manara A, Shemie SD, Large S, et al. Maintaining the permanence principle for death during in situ normothermic regional perfusion for donation after circulatory death organ recovery: a United Kingdom and Canadian proposal. Am J Transplant 2020;20:2017-25. https://doi.org/10.1111/ajt.15775.