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Five-year outcomes of machine perfusion versus static cold storage in controlled donation after circulatory death kidney transplantation: a binational cohort study

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While hypothermic machine perfusion reduces delayed graft function (DGF) after kidney transplantation, its long-term benefits in controlled donation after circulatory death (DCD) are uncertain in real-world practice. We evaluated whether perfusion improves 5-year death-censored graft survival compared to static cold storage in DCD by benchmarking outcomes against those of donation after brain death (DBD). After analyzing the United Network for Organ Sharing and Swiss Transplant Cohort Study registries, we created a 1:1 propensity-score-matched cohort to balance baseline characteristics. Among 44,552 DCD recipients (34,739 with perfusion; 9,813 with cold storage) and 180,898 DBD controls, the matched 5-year death-censored graft survival rate was 84.8% with perfusion versus 87.4% with cold storage (hazard ratio 1.08; P = 0.19). Perfusion significantly reduced the rate of DGF (35.7% vs. 44.9%; P <

0.001), while the rates of primary nonfunction and acute rejection were comparable. Both DCD groups achieved long-term outcomes equivalent to those of the DBD cohort. In conclusion, while machine perfusion confers a substantial early reduction in delayed graft function, static cold storage continues to deliver excellent 5-year graft survival. Both strategies yield excellent long-term outcomes comparable to those of DBD transplants. Crucially, these findings support expanding DCD programs to include older donors as a vital strategy to increase transplantation rates and reduce waitlist mortality. To optimize outcomes in these older DCD grafts, clinicians should aim to limit donor comorbidity, keep total ischemia time below 12–15 h, and utilize continuous rather than end-ischemic machine perfusion whenever logistically feasible.

KEYWORDS

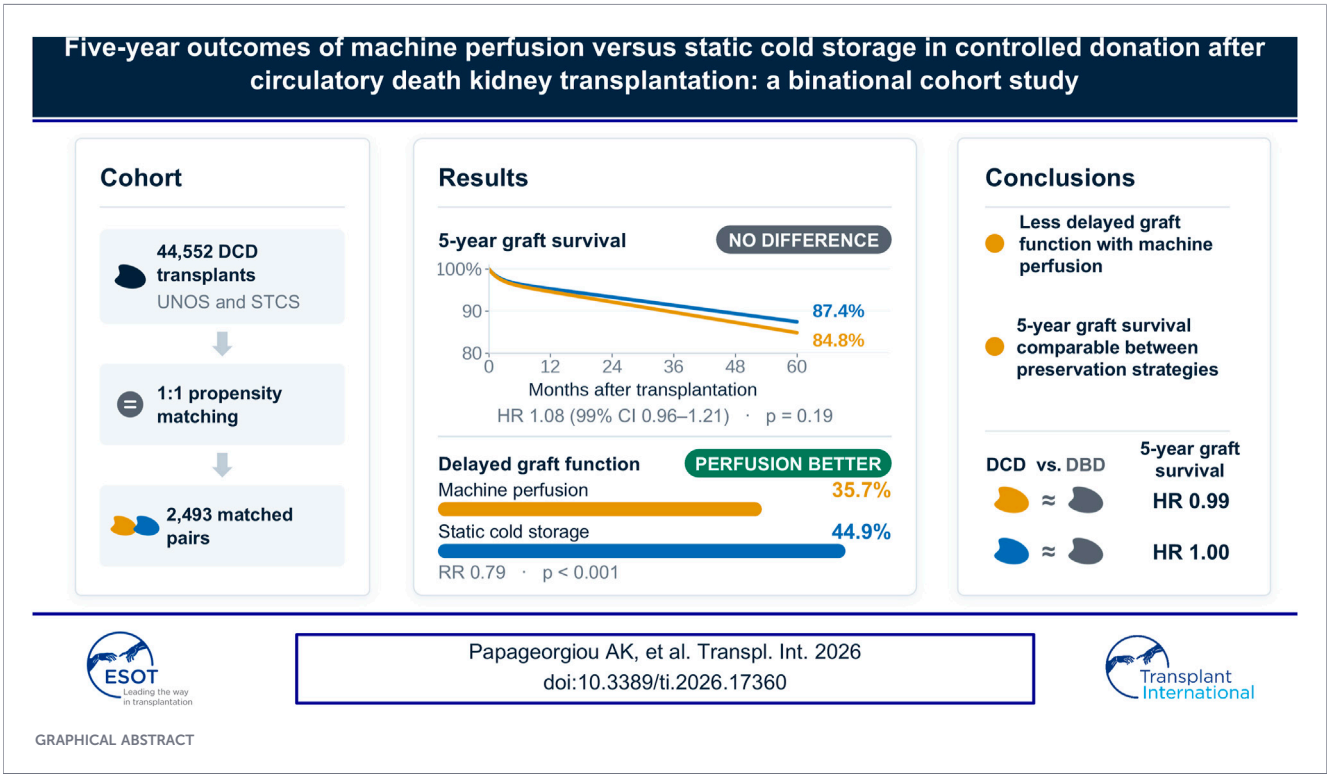
cold storage, DCD, DGF, machine perfusion, survival analysis

Introduction

Chronic kidney disease affects over 800 million individuals globally and frequently progresses to kidney failure requiring dialysis or transplantation [1, 2]. Transplantation confers a survival benefit over dialysis, but the persistent shortage of donor organs prolongs waiting times and increases waitlist mortality [3]. To expand the donor pool, transplant centers increasingly use kidneys from donation after circulatory death (DCD) [4, 5].

To mitigate preservation injury, machine perfusion has a longer clinical track record in kidney transplantation than in any other solid organ, and two modalities now dominate: hypothermic machine perfusion (HMP) and (sub) normothermic machine perfusion (NMP). By continuously perfusing the kidney, the goal is to limit cellular damage, maintain metabolism, and reduce delayed graft function (DGF) [6]. The same approach has since been extended to other solid organs [7–10]. The clinical adoption of HMP was driven by the paired-kidney Machine Preservation Trial, which compared continuous HMP from the donor hospital with the standard (non-perfused) static cold storage (SCS) and showed reduced DGF and improved 1-year graft survival [11]; the 10-year follow-up showed that the graft survival benefit persisted, with the largest effect seen in expanded-criteria grafts [12]. In contrast, end-ischemic perfusion, applied after a period of cold storage, has not produced these benefits, whether as oxygenated HMP in expanded-criteria donors or as 1 h of NMP in DCD kidneys [13, 14]. A 2024 Cochrane review accordingly reports high-certainty evidence of the benefits of continuous HMP but not end-ischemic NMP [6].

Whether these benefits extend to long-term graft survival in controlled DCD under real-world conditions remains unclear [6].



GRAPHICAL ABSTRACT

Prior studies have predominantly focused on mixed deceased donors or short-term endpoints [6, 11, 12]. DCD kidneys are particularly susceptible to ischemia-reperfusion injury because of obligatory warm ischemia during circulatory arrest [13], making preservation a clinically important question.

To address this knowledge gap, we analyzed data from the United Network for Organ Sharing (UNOS) in the United States and the Swiss Transplant Cohort Study (STCS) in Switzerland, aiming to provide large-scale evidence on the long-term viability of machine perfusion for DCD kidneys.

Materials and methods

Study population and data sources

De-identified data from the UNOS (obtained 18 August 2023) and the STCS (obtained 31 January 2025) were analyzed. Adult recipients of a first deceased-donor kidney transplant were included. All DCD donors were controlled DCD (Maastricht category III); uncontrolled DCD is not routinely practiced in the United States or Switzerland. The study was approved by the Cantonal Ethics Committee Zurich (BASEC 2023-01709) and was conducted in accordance with the Declaration of Helsinki. The population was divided into three groups: an HMP group (DCD kidneys preserved by machine perfusion), a DCD control group (DCD kidneys preserved by SCS), and a DBD control group. The overall DBD cohort was specifically included to serve as a qualitative, real-world clinical benchmark. While heterogeneous in its preservation strategies, this allowed the DCD outcomes to be contextualized against the historical standard of deceased organ donation, rather than serving as a direct mechanistic comparator for perfusion.

The study period for the UNOS registry cohort extended from October 1987 to August 2023. The study period for the Swiss Transplant Cohort Study (STCS) cohort extended from January 2008 to January 2025. Of note, to specifically isolate the effects of static cold storage and hypothermic machine perfusion, all cases utilizing normothermic regional perfusion (NRP) were explicitly excluded from the STCS cohort. Furthermore, although NRP was introduced in the United States approximately in the year 2020, its utilization remained exceptionally rare throughout our specified UNOS study period[15, 16]. Consequently, NRP does not represent a meaningful confounder in this dataset.

Preservation-method ascertainment

Each registry records preservation as either machine perfusion or SCS. Neither registry reliably distinguishes continuous HMP initiated at the donor hospital from end-ischemic perfusion initiated at an organ-procurement-organization (OPO) hub or recipient center after cold storage transport. In the United States, perfusion is commonly commenced after transport rather than at the donor hospital. In our experience in Switzerland, continuous perfusion from procurement is more common. Because the UNOS cohort contributes the vast majority of recipients, pooled estimates predominantly reflect United States practices; the Swiss subcohort was also examined separately as a subgroup analysis to confirm the results from the UNOS database.

Outcomes and definitions

The primary outcome was 5-year DCGS (time from transplantation to graft failure; recipients who died with a functioning graft were censored). The secondary outcomes were DGF, overall patient survival, acute rejection, and 12-month eGFR. DGF was defined, per registry convention, as the need for dialysis within the first 7 days after transplantation; because both registries record this as a single binary field, dialysis performed solely for hyperkalemia or volume overload could not be separately excluded, a non-specificity that applies equally to both preservation groups. Graft survival in UNOS followed UNOS guidance (Supplementary Material 1), and in STCS, it followed the registry definition. Acute rejection was defined as any rejection requiring anti-rejection therapy (UNOS) or biopsy-proven acute rejection (STCS). eGFR was calculated with the CKD-EPI 2021 creatinine equation.

Statistical analysis

The propensity-score-matched cohort was the primary analytic population for all survival inferences. Continuous variables were compared with a Student's t-test or a Mann–Whitney U test, and categorical variables with a χ^2 or a Fisher's exact test. To minimize selection bias, 1:1 nearest-neighbor matching without replacement was performed using a logistic regression propensity model including nine pre-transplant donor and recipient covariates: recipient age, dialysis vintage, donor age, donor terminal creatinine, donor hypertension, donor diabetes, HLA mismatch, cold ischemia time, and functional warm ischemia time. A caliper of 0.2 SD of the logit of the propensity score was applied. Balance was assessed by absolute standardized mean differences (SMD), which were <0.1 for all matched covariates; before-and-after SMDs are provided in Supplementary Table S3 and Supplementary Figure S1. Separate matches were generated for each pairwise comparison (HMP vs. SCS; HMP vs. DBD; SCS vs. DBD).

DCGS and patient survival were estimated using the Kaplan-Meier method with log-rank tests; cause-specific Cox proportional hazards models (treating death with a functioning graft as a censoring event) yielded hazard ratios (HR) with 99% CIs, with the proportional-hazards assumption verified using Schoenfeld residuals. Unadjusted Kaplan–Meier estimates and univariable and multivariable Cox models in the unmatched cohort are reported only to characterize confounding by indication and are not the basis for the study's inferences; throughout, "matched" denotes propensity-score-matched comparisons and "adjusted" denotes multivariable Cox modeling, and the two are not used interchangeably. Missing data were handled by complete-case analysis, and the number of recipients with available data is reported for each outcome. No formal sample-size calculation was performed; all eligible recipients during the study period were included. Given the large sample size, effect sizes and 99% CIs were prioritized over P values to separate clinical relevance from statistical significance. The analyses used R; a two-sided $P < 0.05$ was considered significant.

TABLE 1 Patient characteristics. Functional warm ischemia time is reported in minutes.

	DCD donors			DBD[1]
Characteristics	Cold storage N = 9,813[1]	Machine perfusion N = 34,739[1]	p-value[2]	
Study cohort			<0.001	
Swiss	92/9,813 (0.9%)	153/34,739 (0.4%)		435/180,898 (0.2%)
UNOS	9,721/9,813 (99%)	34,586/34,739 (100%)		180,463/180,898 (100%)
Recipient age (Years)	54 (13)	55 (12)	<0.001	53 (13)
Recipient sex			<0.001	
F	3,887/9,721 (40%)	13,026/34,586 (38%)		71,227/180,463 (39%)
M	5,834/9,721 (60%)	21,560/34,586 (62%)		109,236/180,463 (61%)
Recipient BMI	28.3 (5.4)	28.8 (5.4)	<0.001	28.2 (5.5)
Dialysis vintage (Years)	4.71 (3.27)	4.24 (2.90)	<0.001	4.23 (3.19)
Donor age (Years)	36 (16)	41 (14)	<0.001	39 (16)
Donor creatinine (mg/dL)	0.89 (0.81)	1.03 (0.89)	<0.001	1.30 (1.20)
Donor hypertension	2,133/9,664 (22%)	10,156/34,327 (30%)	<0.001	49,813/173,378 (29%)
Donor diabetes	607/9,721 (6.2%)	2,925/34,556 (8.5%)	<0.001	14,892/175,222 (8.5%)
Functional warm ischemia	20 (12)	20 (15)	<0.001	
Cold ischemia time	16 (8)	21 (8)	<0.001	18 (9)
HLA mismatches (0-6)			<0.001	
0	520/9,689 (5.4%)	1,114/34,566 (3.2%)		10,915/179,176 (6.1%)
1	117/9,689 (1.2%)	331/34,566 (1.0%)		2,756/179,176 (1.5%)
2	432/9,689 (4.5%)	1,559/34,566 (4.5%)		7,415/179,176 (4.1%)
3	1,379/9,689 (14%)	4,881/34,566 (14%)		23,455/179,176 (13%)
4	2,596/9,689 (27%)	9,811/34,566 (28%)		48,016/179,176 (27%)
5	3,209/9,689 (33%)	11,634/34,566 (34%)		57,904/179,176 (32%)
6	1,436/9,689 (15%)	5,236/34,566 (15%)		28,715/179,176 (16%)
Delayed graft function	4,775/9,813 (49%)	13,991/34,739 (40%)	<0.001	43,239/180,898 (24%)
Primary non-function	121/9,813 (1.2%)	453/34,739 (1.3%)	0.6	2,133/180,898 (1.2%)
Acute rejection (1 Year)	462/6,580 (7.0%)	1,839/23,493 (7.8%)	0.030	12,961/132,037 (9.8%)

Cold ischemia time is reported in hours.
[1]n/N (%); Mean (SD).
[2]Pearson's Chi-squared test; Wilcoxon rank sum test.

Results

Patient characteristics

A total of 44,552 controlled DCD kidney transplant recipients were analyzed: 9,813 (22%) were preserved with static cold storage (SCS) and 34,739 (78%) were preserved with hypothermic machine perfusion (HMP). The DBD reference cohort comprised 180,898 recipients. Baseline donor and recipient characteristics for all three cohorts are shown in Table 1. The HMP group carried a higher kidney-donor risk profile: donors were older (41 ± 14 vs. 36 ± 16 years; P < 0.001) and more frequently had hypertension (30% vs. 22%; P < 0.001) and diabetes mellitus (8.5% vs. 6.2%; P < 0.001), with a higher mean terminal creatinine level (1.03 vs. 0.89 mg/dL). Cold ischemia time was longer with HMP (mean, 21 vs. 16 h), whereas functional warm ischemia time was comparable (mean 20 min in both DCD groups).

Unadjusted death-censored graft survival

In the unadjusted analysis, the 5-year DCGS was 86.2% (99% CI, 85.8–86.7) with HMP and 87.9% (99% CI, 87.0–88.7) with SCS (Figure 1A); over the full follow-up period, the unadjusted hazard ratio (HR) for graft failure with HMP versus SCS was 1.12 (99% CI, 1.03–1.22; P = 0.001). Compared with the DBD reference cohort (5-year DCGS 85.5%; 99% CI, 85.3–85.7), unadjusted survival was comparable for HMP (HR 0.98; 99% CI, 0.95–1.01; P = 0.24) and SCS (HR 0.88; 99% CI, 0.83–0.93;

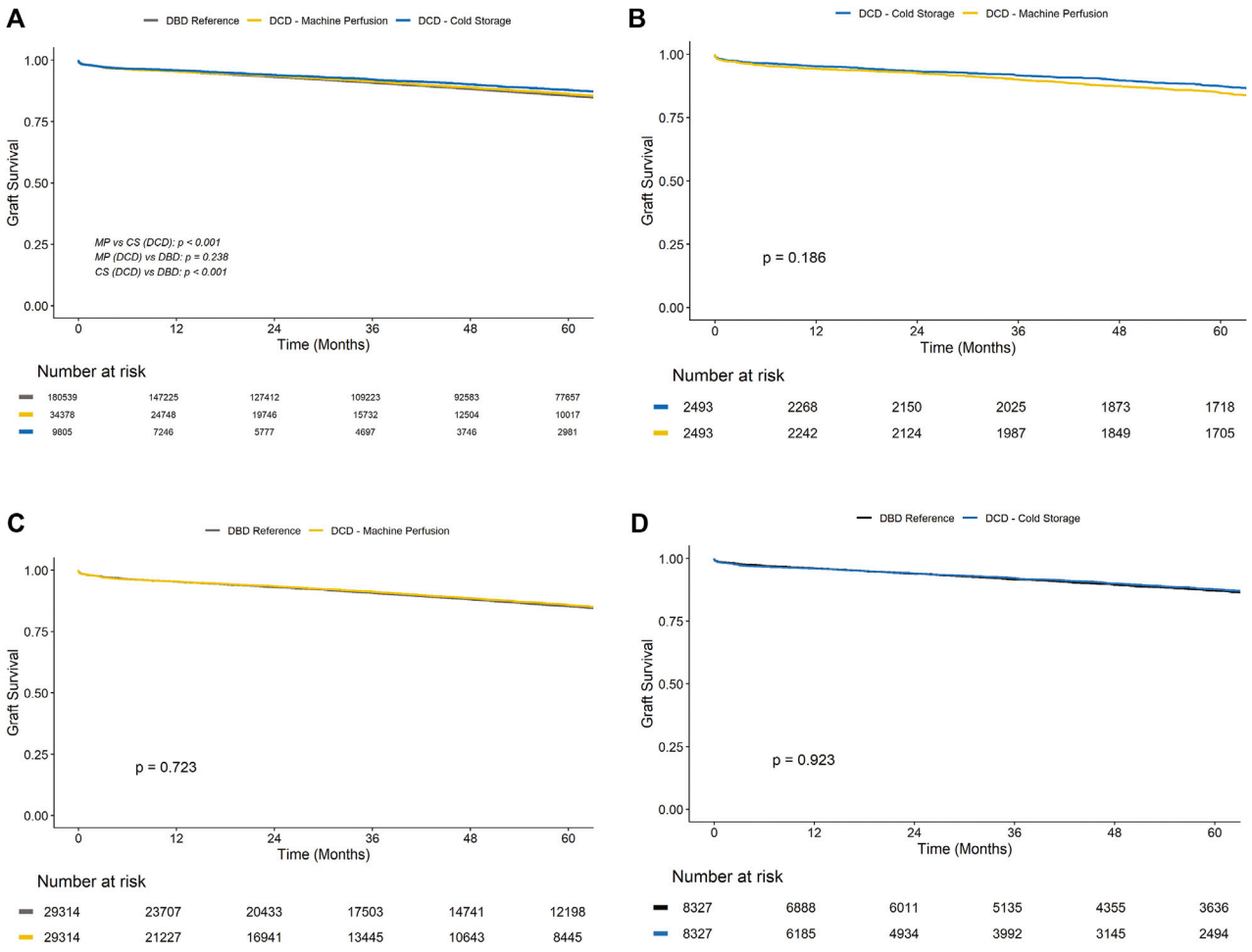


FIGURE 1
Kaplan-Meier estimates of death-censored graft survival across preservation methods. **(A)** Unadjusted comparison of graft survival stratified by preservation method (machine perfusion vs. cold storage) and donor type (DCD vs. DBD reference). **(B)** Propensity score-matched comparison specifically evaluating DCD kidneys preserved via machine perfusion versus DCD kidneys preserved via cold storage. **(C)** Propensity score-matched comparison of DCD kidneys preserved via machine perfusion versus the DBD reference cohort. **(D)** Propensity score-matched comparison of DCD kidneys preserved via cold storage versus the DBD reference cohort. Abbreviations: DCD, donation after circulatory death; DBD, donation after brain death.

P < 0.001), consistent with the preferential allocation of cold storage to lower-risk grafts.

Univariate and multivariable analysis

In univariate Cox regression (Supplementary Material 2), HMP was associated with a higher risk of graft failure than SCS (HR 1.12; 99% CI, 1.03–1.22; P < 0.001), with donor hypertension and diabetes being the strongest predictors of graft loss. In the multivariable model (Supplementary Table S2), preservation modality was no longer associated with graft survival (HR 0.96; 99% CI, 0.85–1.08; P = 0.40). This reversal is consistent with confounding by indication, perfusion having been directed toward higher-risk donors. Donor diabetes (HR 1.37; 99% CI, 1.15–1.64; P < 0.001) and hypertension (HR 1.26; 99% CI, 1.12–1.42; P < 0.001), together with donor age and recipient BMI, remained independent predictors of graft failure.

Propensity score matched analysis

Propensity score matching achieved good balance for donor and recipient characteristics (Table 2), with the exception of Cold Ischemia Time (SMD = 0.188) (Supplementary Material 4). While formal hypothesis testing yielded statistically significant differences for certain covariates (e.g., cold ischemia time and functional warm ischemia time) in the matched cohort, these differences were strictly driven by the high statistical power of the large sample size (N = 4,986). The absolute clinical differences were negligible (e.g., identical mean warm ischemia times of 21 min). Balance was therefore more appropriately confirmed via absolute standardized mean differences (SMD), which remained robust.

In the matched comparison between DCD groups, 5-year DCGS was 84.8% (99% CI, 83.3–86.2) with HMP and 87.4% (99% CI, 86.1–88.8) with SCS (Figure 1B); the corresponding HR of 1.08 (99% CI, 0.96–1.21; P = 0.19) indicated no significant

TABLE 2 Baseline characteristics of the propensity-score-matched cohort.

Characteristics	Overall N = 4,986[1]	Cold storage N = 2,493[1]	Machine perfusion N = 2,493[1]	p-value[2]
Recipient age (Years)	53 (13)	53 (13)	53 (13)	>0.9
Dialysis vintage (Years)	4.39 (3.08)	4.41 (3.08)	4.38 (3.07)	0.8
Donor age (Years)	34 (15)	34 (15)	34 (15)	0.2
Donor creatinine (mg/dL)	0.90 (0.90)	0.86 (0.55)	0.95 (1.15)	0.019
Donor hypertension	881 (18%)	438 (18%)	443 (18%)	0.9
Donor diabetes	238 (4.8%)	108 (4.3%)	130 (5.2%)	0.2
Functional warm ischemia (min)	21 (14)	21 (12)	21 (15)	<0.001
Cold ischemia time (hours)	16 (9)	15 (7)	17 (9)	<0.001
HLA mismatches (0-6)				0.004
0	178 (3.6%)	106 (4.3%)	72 (2.9%)	
1	68 (1.4%)	41 (1.6%)	27 (1.1%)	
2	239 (4.8%)	117 (4.7%)	122 (4.9%)	
3	748 (15%)	367 (15%)	381 (15%)	
4	1,411 (28%)	655 (26%)	756 (30%)	
5	1,630 (33%)	843 (34%)	787 (32%)	
6	712 (14%)	364 (15%)	348 (14%)	

[1]Mean (SD); n.
[2]Wilcoxon rank sum test; Pearson's Chi-squared test (%).

difference in graft survival after balancing baseline donor and recipient characteristics. Matching against the DBD reference confirmed parity: HMP versus DBD, 85.8% (99% CI, 85.3–86.4) versus 85.2% (99% CI, 84.7–85.7) (HR 0.99; 99% CI, 0.95–1.03; P = 0.72; Figure 1C); and SCS versus DBD, 87.7% (99% CI, 86.8–88.7) versus 87.3% (99% CI, 86.4–88.1) (HR 1.00; 99% CI, 0.92–1.09; P = 0.9; Figure 1D).

Patient survival

In the matched cohort, 5-year patient survival was 82.4% (99% CI, 81.4–83.4) with HMP and 81.2% (99% CI, 80.2–82.3) with SCS (Figure 2A); the corresponding HR was 0.92 (99% CI, 0.86–0.97; P = 0.005).

Delayed graft function, acute rejection, and glomerular filtration rate at 12 months

HMP was associated with lower DGF than SCS in both the unadjusted (40% vs. 49%; both exceeding the DBD reference of 24%) and matched (35.7% vs. 44.9%; P < 0.001; Figure 2B) comparisons. Primary non-function was low and similar between DCD groups (1.3% vs. 1.2%). One-year acute rejection, recorded in recipients with available data (Table 1), occurred in 7.0% of SCS (462/6,580) and 7.8% of HMP recipients (1,839/23,493) (P = 0.030); in the matched cohort, rejection rates were comparable between HMP (9.9%) and SCS (9.5%) recipients and similar to the matched DBD benchmark (9.8%) (Figure 2B). At 12 months, matched SCS achieved a slightly higher mean eGFR than HMP (62.7 ± 22.2 vs. 60.5 ± 21.1 mL/min/1.73 m^2; P = 0.002), with the DBD reference being 60.4 ± 22.0 mL/min/1.73 m^2.

Swiss subcohort (subgroup analysis)

Given that the combined analysis is largely driven by the UNOS dataset, we performed separate evaluations of both registries. As expected, analyzing the UNOS database independently did not alter the primary findings or conclusions.

In the Swiss subcohort, baseline DGF was substantially higher, yet HMP remained superior to SCS (55% vs. 69%; P = 0.0051). Despite this, 5-year DCGS was excellent and comparable between preservation groups (89.8% vs. 86.3%; HR 0.86; 99% CI, 0.36–2.02; P = 0.7; Figure 2C), as was 5-year patient survival (87.8% vs. 89.5%; HR 1.23; 99% CI, 0.55–2.74; P = 0.6; Figure 2D). Trends for all other outcomes were directionally consistent with those of the pooled cohort.

Discussion

Our analysis of the UNOS and STCS registries evaluated 5-year outcomes after controlled DCD kidney transplantation. To our knowledge, this is among the largest long-term registry comparisons of preservation strategies specifically in controlled DCD, and one of the few to benchmark both strategies against a contemporaneous DBD reference. The principal finding was that, after propensity matching, HMP did not improve 5-year death-censored graft survival

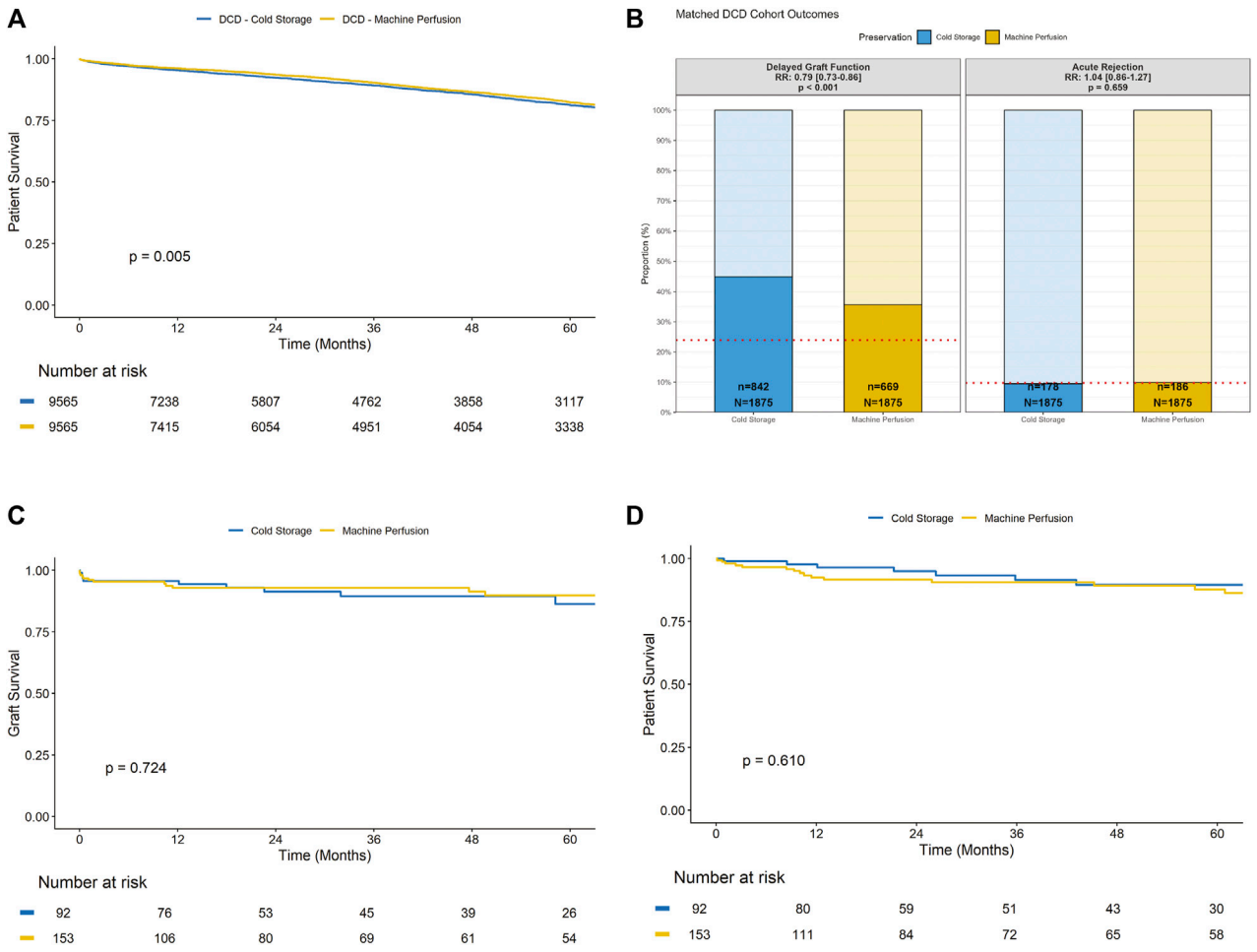


FIGURE 2
Patient survival, matched clinical outcomes, and Swiss cohort analysis. **(A)** Propensity score-matched comparison of overall patient survival between the DCD machine perfusion and cold storage groups. **(B)** Matched comparison of secondary clinical outcomes (delayed graft function and acute rejection). The dotted lines represent the reference rates from the DBD cohort. **(C)** Death-censored graft survival in the Swiss DCD cohort, stratified by preservation method. **(D)** Patient survival in the Swiss DCD cohort, stratified by preservation method. Abbreviations: DCD, donation after circulatory death; DBD, donation after brain death; DGF, delayed graft function.

compared to SCS, despite a robust early reduction in DGF; secondarily, both DCD preservation strategies achieved graft and patient survival rates equivalent to the DBD reference. Thus, within contemporary controlled DCD practice, as captured by these registries, the early protective effect of perfusion did not translate into a long-term graft survival advantage.

Because acute kidney injury is itself a recognized driver of progressive chronic kidney disease in native kidneys [17], a central question was whether the early ischemic insult that perfusion mitigates alters the long-term trajectory of the allograft; our data indicate that it does not. The likely mechanism is a functional "catch-up": although DCD grafts preserved with SCS had higher initial DGF, their 5-year survival was identical to that of perfused grafts, and 12-month eGFR was excellent in both DCD groups and comparable with DBD. Five-year eGFR was not captured by the registries; therefore, this functional parity is established at 12 months rather than at the survival endpoint. Acute rejection did not differ between the preservation strategies or between DCD and DBD, arguing against the concern that greater reperfusion injury with SCS increases alloimmune activation.

These results must be reconciled with high-quality trial evidence. The 2024 Cochrane review found high-certainty evidence that continuous, non-oxygenated HMP from the donor hospital improves short-term graft survival and reduces DGF [6]; consistently, the paired-kidney Machine Preservation Trial retained a graft-survival benefit at 10 years, including for DCD grafts [12], while end-ischemic oxygenated HMP [14] and 1 h of NMP in DCD [13] did not reduce DGF. Our null long-term result does not contradict this evidence; rather, it defines its real-world boundary. Two features of registry data explain the apparent discrepancy: first, perfusion is selectively allocated to higher-risk organs (confounding by indication), which our unadjusted analyses confirm, and matching addresses; second, registry "machine perfusion" is heterogeneous in timing. However, a separate analysis of STCS with common continuous practices demonstrates comparable results to those of the UNOS registry.

While our overall matched cohort comprised relatively young donors (mean age 36–41 years) due to the heavy weighting of the UNOS registry, European programs routinely utilize older controlled DCD donors. This demographic difference is reflected in our Swiss STCS subcohort, which featured substantially older donors. Because donor age is a primary determinant of graft loss, and a previous 10-year trial follow-up demonstrated the greatest perfusion benefit in expanded-criteria grafts (69.6% versus 60.1%) [12]. HMP is frequently viewed as an essential tool for safely expanding the donor pool with older organs. However, our analysis of the STCS cohort demonstrates that excellent long-term graft survival can still be achieved with these older controlled DCD donors using conventional static cold storage. Thus, while a prospective evaluation of continuous HMP in older marginal donors remains warranted, the Swiss data highlight that SCS continues to be a highly viable and effective preservation strategy when machine perfusion is not available.

Interpretation must also account for international heterogeneity in DCD practice. French registry data report inferior long-term survival for uncontrolled (Maastricht I–II) DCD grafts, whereas controlled (Maastricht III) outcomes are less clearly defined [18]. Both the United States and Switzerland practice only controlled DCD, so our cohorts are free of the higher ischemic burden of uncontrolled donation. By demonstrating 5-year DBD parity, our data support the continued expansion of controlled DCD programs. The DGF benefit of upfront perfusion remains clinically and economically relevant, since DGF drives intensive post-transplant dialysis and prolonged admission, and prior analyses have shown that perfusion can be cost-saving [19].

Limitations

First, this is a retrospective registry analysis subject to confounding by indication; although matching mitigated this, unmeasured factors (e.g., surgeon experience, vascular anatomy, and unrecorded KDRI components such as donor height, weight, and cause of death) could not be excluded. Importantly, potential selection bias regarding the decision to utilize HMP remains a key limitation. In the United States, HMP practices vary considerably among Organ Procurement Organizations (OPOs), with some centers selectively perfusing specific kidneys based on local, unrecorded protocols, which introduces an inherent OPO-level selection bias.

Second, crucial details regarding preservation practices and logistics lack granularity within the UNOS registry. Perfusion timing (continuous versus end-ischemic) and total static cold storage duration within the HMP group could not be fully resolved. The registry does not systematically capture the specific type of pump utilized, the administration of active oxygenation, or the precise sequence of transportation. Crucially, however, our primary outcome of 5-year graft survival demonstrated equivalent results between the preservation cohorts. Therefore, this primary conclusion remains robust irrespective of the specific perfusion modalities utilized. Conversely, we agree that variations in these unmeasured perfusion strategies could differentially influence the rate of delayed graft function (DGF), representing a limitation when interpreting the magnitude of early functional benefits. Furthermore, the lack of granular data restricted our ability to perfectly harmonize and contrast the specific HMP protocols between the Swiss (STCS) and US (UNOS) cohorts. Nevertheless, a separate analysis of the STCS database confirms the findings of the UNOS analysis, despite significant variance in donor and recipient characteristics between the two countries, treatment strategies, insurance coverage, and follow-up. Finally, because 5-year outcomes necessarily derive from earlier transplants, the cohort underrepresents the most recent shift toward continuous and explicitly oxygenated perfusion; this temporal mismatch should be borne in mind when generalizing to current practices.

Third, the DBD reference was analyzed as a single group and not stratified by preservation method; therefore, it reflects mixed preservation rather than a pure cold storage benchmark. Fourth, DGF, acute rejection, and eGFR were ascertained from registry fields with variable completeness, and DGF could not be restricted by dialysis indication. Fifth, the Swiss subcohort comprised only 245 DCD recipients (0.5% of the total sample size) and was underpowered for independent inference; the pooled estimates therefore chiefly reflect United States practices, and the Swiss data should be regarded as directional external validation rather than an equal binational comparator.

Importantly, our findings have direct implications for organ utilization policies. Currently, a significant proportion of potentially viable kidneys from older DCD donors, or those with concurrent risk factors such as acute kidney injury (AKI), are discarded. As we recently demonstrated in a comprehensive meta-analysis, while DCD grafts with AKI carry a higher risk of delayed graft function, their long-term survival remains comparable to those without AKI [20]. Similarly, our current data demonstrate that DCD kidneys—even when preserved with standard static cold storage—achieve 5-year graft survival equivalent to the overall DBD reference pool. Given the significant mortality associated with remaining on the transplant waiting list, these results strongly advocate for the greater utilization of older and marginal DCD donors. Rather than discarding these organs based on perceived ischemic risks, expanding DCD utilization represents a safe, viable, and necessary strategy to reduce waiting times and decrease waitlist mortality.

Based on the encouraging short- and medium-term results reported in several European countries, kidneys from older DCD donors can achieve excellent graft outcomes, provided that appropriate selection and preservation criteria are applied. These include continuous HMP, limited donor comorbidity, and a total ischemia time preferably below 12–15 h [21–23].

We also advocate for the increased acceptance of kidneys from DCD donors over 50 years of age using continuous HMP, whenever logistically feasible. Although embracing this approach requires a shift in mindset among nephrologists and transplant surgeons, it represents a crucial strategy to substantially increase transplantation activity. Maximizing this potential also depends heavily on local and national allocation frameworks. Appropriate donor-recipient age

matching and allocation strategies designed to minimize ischemia time are particularly relevant for older DCD organs [21–23]. For instance, the Eurotransplant Senior Program (ESP) is a highly effective "old-for-old" allocation strategy aimed at facilitating the transplantation of kidneys from older donors while strictly limiting cold ischemia time [24].

Conclusion

In controlled DCD kidney transplantation, HMP substantially reduces DGF, but does not improve 5-year death-censored graft survival versus SCS in real-world, binational practices, and both strategies achieve DBD-equivalent outcomes. These findings support the continued expansion of controlled DCD programs and affirm SCS as a valid alternative when HMP is unavailable. Most importantly, by demonstrating that DCD kidneys achieve long-term survival comparable to those of the standard DBD pool, this study advocates for the broader utilization of older and marginal DCD grafts as a safe and necessary strategy to increase overall transplantation rates and reduce waitlist mortality. Finally, our results suggest that continuous, rather than end-ischemic, perfusion delivery may be required to reproduce the long-term survival benefit observed in randomized trials, a hypothesis that warrants prospective evaluation.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: Data are not publicly available owing to registry restrictions and data-use agreements with UNOS and the STCS. Requests for access should be directed to the respective registries.

Ethics statement

The study was approved by the Cantonal Ethics Committee Zurich (BASEC 2023-01709). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

Research idea and study design: AP, FK, JO, and DE. Data acquisition: all authors. Data analysis and interpretation: AP, FK, MS, JJ, BM, JB, DG, MP, TP, DJ, JO, and DE. Statistical analysis: AP, FK, MS, and DE. Supervision and mentorship: DE and JO. Each author contributed important intellectual content during drafting or critical revision, approved the final version, and accepts accountability for the integrity of the work. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. Artificial-intelligence-based tools were used for language editing and formatting; no AI tool contributed to data analysis, interpretation or authorship.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontierspartnerships.org/articles/10.3389/ti.2026.17360/full#supplementary-material

References

1. Bello AK, Okpechi IG, Osman MA, Cho Y, Htay H, Jha V, et al. Epidemiology of haemodialysis outcomes. *Nat Rev Nephrol* (2022) 18(6):378–95. doi: 10.1038/s41581-022-00542-7

2. Kovesdy CP. Epidemiology of chronic kidney disease: an update 2022. *Kidney Int Suppl* (2011) 12(1):7–11. doi: 10.1016/j.kisu.2021.11.003

3. The United States Renal Data System. The United States renal data system (2024). Available online at: https://usrds-adr.niddk.nih.gov/2024/end-stage-renal-disease/6-mortality (Accessed December 23, 2024).

4. Nita GE, Gopal JP, Khambalia HA, Moinuddin Z, van Dellen D. Kidney transplantation from donors with acute kidney injury: are the concerns justified? A systematic review and meta-analysis. *Transpl International : Official Journal Eur Soc Organ Transplant* (2023) 36:11232. doi: 10.3389/ti.2023.11232

5. Husain SA, Motter JD, Stewart D, Levan ML, Bae S, Parent B, et al. Changes in organ donation after circulatory death in the United States. *JAMA* (2026) 335(12):1087–9. doi: 10.1001/jama.2026.0976

6. Tingle SJ, Thompson ER, Figueiredo RS, Moir JA, Goodfellow M, Talbot D, et al. Normothermic and hypothermic machine perfusion preservation *versus* static cold storage for deceased donor kidney transplantation. *Cochrane Database Syst Rev* (2024) 7(7):CD011671. doi: 10.1002/14651858.CD011671.pub3

7. Eshmuminov D, Becker D, Bautista Borrego L, Hefti M, Schuler MJ, Hagedorn C, et al. An integrated perfusion machine preserves injured human livers for 1 week. *Nat Biotechnol* (2020) 38:189–98. doi: 10.1038/s41587-019-0374-x

8. Nasralla D, Coussios CC, Mergental H, Akhtar MZ, Butler AJ, Ceresa CDL, et al. A randomized trial of normothermic preservation in liver transplantation. *Nature* (2018) 557(7703):50–6. doi: 10.1038/s41586-018-0047-9

9. Nasralla D, Mergental H, Jassem W. A randomised controlled trial of normothermic liver perfusion *versus* cold storage in human liver transplantation. *Transpl international. J Conf Abstract.* (2015) 28:285. doi: 10.1111/tri.12702

10. van Rijn R, Schurink IJ, de Vries Y, van den Berg AP, Cortes Cerisuelo M, Darwish Murad S, et al. Hypothermic machine perfusion in liver transplantation - a randomized trial. *N Engl J Med* (2021) 384(15):1391–401. doi: 10.1056/NEJMoa2031532

11. Moers C, Smits JM, Maathuis MH, Treckmann J, van Gelder F, Napieralski BP, et al. Machine perfusion or cold storage in deceased-donor kidney transplantation. *N Engl J Med* (2009) 360(1):7–19. doi: 10.1056/NEJMoa0802289

12. Schutter R, Moers C, Jochmans I, Gallinat A, Paul A, Treckmann J, et al. Cold perfusion vs. static cold storage of deceased-donor kidneys - at 10 years. *N Engl J Med* (2025) 393(18):1859–61. doi: 10.1056/NEJMc2406608

13. Hosgood SA, Callaghan CJ, Wilson CH, Smith L, Mullings J, Mehew J, et al. Normothermic machine perfusion *versus* static cold storage in donation after circulatory death kidney transplantation: a randomized controlled trial. *Nat Med* (2023) 29(6): 1511–9. doi: 10.1038/s41591-023-02376-7

14. Husen P, Boffa C, Jochmans I, Krikke C, Davies L, Mazilescu L, et al. Oxygenated end-hypothermic machine perfusion in expanded criteria donor kidney transplant: a randomized clinical trial. *JAMA Surg* (2021) 156(6):517–25. doi: 10.1001/jamasurg.2021.0949

15. Sellers MT, Philip JL, Brubaker AL, Cauwels RL, Croome KP, Hoffman JR, et al. Normothermic regional perfusion experience of organ procurement organizations in the US. *JAMA Netw Open* (2024) 7(10):e2440130. doi: 10.1001/jamanetworkopen.2024.40130

16. Bekki Y, Croome KP, Myers B, Sasaki K, Tomiyama K. Normothermic regional perfusion can improve both utilization and outcomes in DCD liver, kidney, and pancreas transplantation. *Transpl Direct* (2023) 9(3):e1450. doi: 10.1097/TXD.0000000000001450

17. Chan GC, Chow KM. Should we use kidneys from donors with acute kidney injury for renal transplantation? *Nephrology (Carlton)* (2020) 25(2):105–15. doi: 10.1111/nep.13679

18. Biomedecine. The medical and scientific report of the collection and transplantation in France. Available online at: https://rams.agence-biomedecine.fr/greffe-renale-0 (Accessed January 15, 2026).

19. Groen H, Moers C, Smits JM, Treckmann J, Monbaliu D, Rahmel A, et al. Cost-effectiveness of hypothermic machine preservation *versus* static cold storage in renal transplantation. *Am Journal Transplantation* (2012) 12(7):1824–30. doi: 10.1111/j.1600-6143.2012.04030.x

20. Trachsel C, Kalt F, Jonas JP, Rössler F, Lopez-Lopez V, Hübel K, et al. Outcomes of kidney transplants from donors after circulatory death with acute kidney injury: a systematic review. *Curr Transplant Rep* (2025/10/28 2025) 12(1):40. doi: 10.1007/s40472-025-00496-2

21. de Boer SE, Tegzess E, Kremer D, Bemelman FJ, Christiaans MHL, Hilbrands LB, et al. Comparable outcomes for old, older, and very old deceased donors in old kidney transplant recipients. *Am Journal Transplantation* (2026) 26(5):1087–99. doi: 10.1016/j.ajt.2026.01.003

22. Jochmans I, Brat A, Davies L, Hofker HS, van de Leemkolk FEM, Leuvenink HGD, et al. Oxygenated *versus* standard cold perfusion preservation in kidney transplantation (COMPARE): a randomised, double-blind, paired, phase 3 trial. *Lancet* (2020) 396(10263):1653–62. doi: 10.1016/S0140-6736(20)32411-9

23. Jochmans I, Hessheimer AJ, Neyrinck AP, Paredes D, Bellini MI, Dark JH, et al. Consensus statement on normothermic regional perfusion in donation after circulatory death: report from the European society for organ Transplantation's transplant learning journey. *Transpl International : Official Journal Eur Soc Organ Transplant* (2021) 34(11): 2019–30. doi: 10.1111/tri.13951

24. Smits JM, Persijn GG, van Houwelingen HC, Claas FH, Frei U. Evaluation of the Eurotransplant Senior program. The results of the first year. *Am Journal Transplantation* (2002) 2(7):664–70. doi: 10.1034/j.1600-6143.2002.20713.x