Received: 25 January 2021 | Revised: 25 March 2021 | Accepted: 14 April 2021
DOI: 10.1111/ajt.16617

ORIGINAL ARTICLE

AJT

The organ procurement costs of expanding deceased donor organ acceptance criteria: Evidence from a cost function model

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Funding information
John Sobrato Foundation

A potential solution to the deceased donor organ shortage is to expand donor acceptability criteria. The procurement cost implications of using nonstandard donors is unknown. Using 5 years of US organ procurement organization (OPO) data, we built a cost function model to make cost projections: the total cost was the dependent variable; production outputs, including the number of donors and organs procured, were the independent variables. In the model, procuring one kidney or procuring both kidneys from double/*en bloc* transplantation from a single-organ donor resulted in a marginal cost of $55 k (95% confidence interval [CI] $28 k, $99 k) per kidney, and procuring only the liver from a single-organ donor results in a marginal cost of $41 k (95% CI $12 k, $69 k) per liver. Procuring two kidneys for two candidates from a donor lowered the marginal cost to $36 k (95% CI $22 k, $66 k) per kidney, and procuring two kidneys and a liver lowers the marginal cost to $24 k (95% CI $17 k, $45 k) per organ. Economies of scale were observed, where high OPO volume was correlated with lower costs. Despite higher cost per organ than for standard donors, kidney transplantation from nonstandard donors remained cost-effective based on contemporary US data.

KEYWORDS
donors and donation: extended criteria, ethics and public policy, health services and outcomes research, kidney transplantation/nephrology, mathematical model, organ procurement, organ procurement and allocation, organ procurement organization, organ transplantation in general

1 | INTRODUCTION

The shortage of available organs represents a large public health crisis worldwide, including in the United States.[1] One solution is to expand living donation for organs where possible. Another solution is to expand deceased donor organ utilization. The expansion of deceased donor criteria has been an active area of recent research. Comparative studies between the United States and other developed countries including the United Kingdom, Spain, and France have shown that nonstandard donors, including older donors and donation after cardiac death (DCD) donors, are underutilized in the United States, despite evidence showing acceptable transplant outcomes.[2-4] From 2006 through 2018, the use of kidneys from donors age 65 and older remained stagnant below 10%, and discard rates for "lower quality" kidneys (as measured by the Kidney Donor Profile Index [KDPI] >85) remain high at 60%,[5] representing a large

Abbreviations: CI, confidence interval; CMS, Centers for Medicare and Medicaid Services; DBD, donation after brain death; DCD, donation after cardiac death; KDPI, Kidney Donor Profile Index; OACC, organ acquisition cost center; OPO, organ procurement organization; QALY, quality-adjusted life-year; SAC, standard acquisition charge; SRTR, Scientific Registry of Transplant Recipients; US, United States.

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lost opportunity to transplant more patients. Expanding utilization of organs from nonstandard donors represents an opportunity for enhancing access to transplantation. Most discussions have focused on the kidney, the most commonly transplanted organ, although the same arguments have also been made for the liver[6] and thoracic organs.[7] As the bedrock of transplantation is public trust, honoring the gift of life from every consenting donor family by utilizing every organ possible, even if the donor is nonstandard, enhances public trust and may also indirectly increase organ supply by increasing registry enrollment and donor authorization rates.

The precise costs of using nonstandard donors are unknown. Single-center[8] and large consortium-based studies[9] have indicated that kidney transplants from expanded-criteria donors—a specifically defined subset of nonstandard donors who are older and have more comorbidities—cost more in terms of peritransplant and posttransplant care for transplant programs. A sizeable fraction of the increased cost results from an increased incidence of delayed graft function with its associated expenses, longer hospital stays, and slower recovery of the recipient.[10] Similarly, liver transplantation from nonstandard donors is associated with higher costs, as reviewed by Feng and Lai.[6]

Thus far, these studies have not systematically considered how the use of nonstandard donors alters the cost of *organ procurement*. Organ procurement costs, hereafter referred to as organ procurement organization (OPO) costs, are the costs incurred by OPOs—which ultimately are transferred to Medicare and other insurers. A 3-year study performed by the Louisiana Organ Procurement Agency in 1995 reported a 17% increase in direct hospital cost and 30% increase in indirect OPO cost for expanded-criteria donors (compared to standard-criteria donors) on a per-organ basis.[11] However, if we were to calculate the average per-*donor* cost between expanded-criteria and standard-criteria donors, costs are *lower* in expanded-criteria donors (Table 1). We therefore choose to re-interpret these data as follows.

We divide the OPO costs of organs into three parts (Figure 1): (1) the overhead of maintaining an OPO, which is fixed regardless of the number of donors or organs processed; (2) the cost of the donor, which is fixed whether one or multiple organs are procured from the donor, for example, obtaining consent, performing donor work-up, laboratory charges including histocompatibility typing, and donation; and (3) the individual costs of each organ, which is variable depending on the organ, for example, organ-specific work-up (coronary angiograms for hearts, biopsies for individual organs), transportation, and allocation costs. In the case of organ importation/exportation, or transfer of organs between OPOs to facilitate allocation, the exporting OPO passes the cost of the organ and a proportionate fraction of the donor and fixed cost to the importing OPO. That nonstandard donor organs cost more is likely due to lower organ yield per donor, resulting in higher per-organ cost, and a more frequent occurrence of organ importation and exportation. Lindemann et al. have made a similar observation in their analysis of OPO cost between donation after brain death (DBD) versus DCD donors in one specific OPO[12]: although mean cost per donor is the same for DCD and DBD ($32 k), the cost per organ transplanted is higher ($15 k vs. 9 k).

In this study, we calculate OPO costs using a cost function methodology. A cost function approach is simple, intuitive, makes no assumption about how costs are allocated within the OPO's accounting structure, and enables more accurate projections. For instance, if we were to project based on the average cost of a kidney, we would conclude that procuring two additional kidneys would cost an additional two times the average cost, whether they came from one or two donors, or whether they facilitate one (standard, single kidney transplant) or two (double/*en bloc* kidney transplant[13]) transplants. However, procuring two kidneys from one donor clearly costs less than procuring two kidneys from two donors, and allocating two kidneys to one patient clearly costs less than sending them to two different patients. A cost function approach thus gives us the flexibility to estimate the marginal costs across a range of donor yields. We were especially interested in the most expensive scenario: procuring organs from a donor to facilitate a single kidney transplant.

2 | METHODS

Our analysis consists of two parts. In Part 1, we compare donor yields (number of transplants facilitated by each donor) across donor quality, using the deceased donor file of the Scientific Registry of Transplant Recipients (SRTR). The SRTR contains deidentified data on all solid organ transplant donors, candidates, and recipients in the United States. In Part 2, we use data from OPO cost forms[14] to build a cost function which enables us to estimate the marginal cost of organs, accounting for the three types of costs as outlined above.

2.1 | Data

The 58 US OPOs (51 independent, seven hospital based) are nonprofit entities with a federal contract for all activities related to organ

TABLE 1 Difference in OPO cost by donor type (expanded vs. standard criteria): a reinterpretation of cost data from Jaccobi et al.[11]

			Direct hospital cost		Indirect OPO cost	
Donor type	Donors	Organs per donor	Per organ	Per donor[a]	Per organ	Per donor[a]
Expanded	73	3.0	$4963	$14,889	$3504	$10,512
Standard	204	4.3	$4136	$17,784	$2695	$11,589

Abbreviation: OPO, organ procurement organization.
All columns are reproduced from table 3 of Jaccobi et al., except we added costs *per donor*.
[a]Cost per donor: calculated as cost per organ multiplied by average organs per donor.

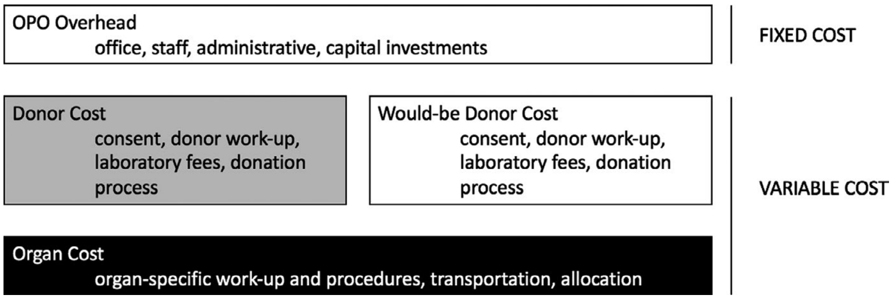

FIGURE 1 Costs of organ procurement (OPO costs): a conceptual breakdown. The types of OPO costs are broken down by the outputs: unmeasured (white boxes), donors (gray box), and organs (black box)

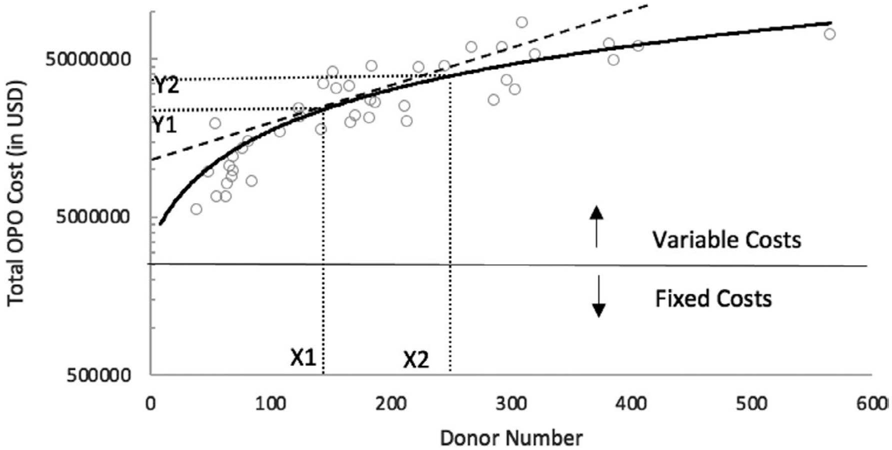

FIGURE 2 Example cost function plot: cost versus donor numbers among 47 organ procurement organizations (OPOs) in 2017, each datapoint representing one OPO. The total cost of production (dependent variable, *y* axis, log-scale) is a function of total production outputs (independent variable, *x* axis). Total costs can be disaggregated into variable costs (costs that vary depending on the production output) versus fixed costs (costs that do not vary, i.e., the *y* intercept, or $5.4 million). At an OPO production output of 166 (median, X1), the marginal is the slope of the tangent line (hatched), or $174 k per donor, whereas the average additional cost for the next 100 donors is (Y2 − Y1)/(X2 − X1), or $194 k per donor. Note that this figure is for illustrative purposes: the numbers differ from our final model outputs which include (1) independent variables other than donor count and (2) data from all 5 years

donation and procurement in a specific geographic area. These activities include evaluating potential donors, obtaining consent, recovering and preserving organs, and transporting organs to transplanting centers. Every year, all 51 independent OPOs are federally mandated to report all costs related to their organ procurement activities to the Centers for Medicare and Medicaid Services (CMS) using form CMS-216–94. We obtained all available cost reports from 2013 through 2017 from a CMS contractor via a Freedom of Information Act request. The cost reports include, among other data, total costs (including administrative and overhead, personnel cost, and specific organ costs; decided by accounting rules; worksheet A, Column 7, Row 26) and total organs retrieved and administratively processed (worksheet S-1). In our analysis, we used the counts of all organs, whether or not they were transplanted ("viable"), and examined in a sensitivity analysis whether specifying viable or nonviable organ changed the results. We supplement cost report data with measures of OPO performance, including donor counts, from center-specific reports released by SRTR and data on local cost of living (Expatistan and CMS Wage Index), as previously described.[14]

2.2 | Cost function

The cost function (Figure 2), or cost curve, is a cornerstone of microeconomics. In classic economic analysis, the total cost of production (dependent variable, *y* axis) is plotted as a function of total production outputs (independent variable, *x* axis). Total cost can be disaggregated into variable costs (costs that vary depending on the production output) and fixed costs (costs that do not vary, i.e., the *y* intercept). The curve also allows for calculation of average costs (total cost/total production) and marginal costs (incremental increase in cost/incremental increase in production).

Economists have used the cost function approach to investigate the cost of health care since the 1980 s. Because health care outputs are manifold, for example, inpatient care, outpatient care, and elective procedures, Grannemann et al.[15] developed a multiple-output cost function wherein the independent (*x* axis) variables include multiple types of production outputs while the dependent variable (*y* axis) is the total cost. This approach has been applied to investigate such areas as the costs borne by Medicare beneficiaries in nursing homes[16] and the cost of dialysis modalities (peritoneal versus hemodialysis).[17]

In our adoption of the multiple-output cost function model, we modeled how total cost (outcome) is related to production outputs, that is, number of donors, organs, and tissues. A production output we cannot measure directly is the number of would-be donors. The SRTR defines donors as donors who have had at least one organ procured; this definition excludes potential donors who may have incurred OPO resources to work-up and consent, but from whom no organ was ultimately procured. Potential DCD donors who did not advance to donation would be an example.[12] We estimated the number of potential donors indirectly by numbers of eligible deaths at each OPO and included it as a covariate in the model. To account for differences in geography and patient population, we included covariates based on our previous work,[14] including year, local price index, and donor case-mix.

2.3 | Analysis

We used a generalized linear equation, incorporating an unstructured covariance matrix to account for the correlation within the same OPO across different years. We modeled the outcome as the natural log of total cost, as is the standard in health economics analyses. Given the small size of the coefficients, we modeled donor and organ numbers as 100 s (for instance, 116 donors would be 1.16). We used a squared term for numbers of donors to capture the curvilinear shape of the cost function (Figure 2). To account for the issue of kidney importing, where an import kidney (donor count =0) would cost the OPO a different sum compared to kidney from a local donor (donor count =1), we added an interaction term between the donor number and kidney number (see Supplemental S1 for further explanation). We collapsed all nonkidney organs into a single variable, as the individual number of livers, hearts, lungs, pancreases, and intestines was small, and the power to detect differences in costs related to other organs was limited.

We made projections for three hypothetical OPOs at three levels of production outputs: 25% percentile, median, and 75% percentile. We use the output of our models (i.e., coefficients) to make the projections. We estimated the marginal cost of each organ at four different level of organ yield (one kidney transplant or one liver transplant per donor [single-organ donor], two kidney transplants per donor, or two kidneys plus one liver transplant per donor). Because organ yield is defined as number of transplants facilitated by an organ, one kidney transplant per donor may refer to two scenarios: (1) only one kidney is procured and transplanted into one patient and (2) both kidneys are procured and transplanted into one patient (double/*en bloc* transplant). Two kidneys per donor, on the other hand, refer to the scenario in which two kidneys are procured and transplanted into two patients. To generate the point estimate and relevant range for these projections, we generated 1000 samples via bootstrapping, fit our model in each sample, made our calculations based on the model outputs (i.e., coefficients) of each sample, and reported the median and 2.5th and 97.5th percentile range (95th confidence interval or 95th CI).

We conducted statistical analyses using SAS 9.4 (Cary, NC). The data reported here have been supplied by the Minneapolis Medical Research Foundation as the contractor for the SRTR. The interpretation and reporting of these data are the responsibility of the authors and in no way should be seen as an official policy of or interpretation by the SRTR or the US government.

3 | RESULTS

3.1 | Donor yield patterns

Of 10 291 deceased donors from whom at least one organ was procured in 2017, 3649 (35%) could be deemed nonstandard on the basis of age, DCD, KDPI >85, or any combination of these factors (Table 2). Standard donors facilitated more transplants than nonstandard donors, however defined. Compared to standard donors, nonstandard donors were more likely to be single-organ donors (9% vs. 30%, $p < .0001$), although the distinction was not marked in non-DCD versus DCD donors. Where older (age ≥60) and KDPI >85 donors resulted in only one transplant, most were liver transplants (91% and 87%, respectively). However, most DCD single-organ donors were kidney donors (75%). Utilization of kidneys was high for DCD donors (83% of DCD donors resulted in kidney transplants) but dropped substantially for older and KDPI >85 donors (only 42% and 35% of older and KDPI >85 donors resulted in kidney transplants, respectively). The reverse was seen for livers: utilization was comparable despite age and KDPI status but decreased substantially for DCD donors (27% compared to 85% in non-DCD donors, $p < .0001$). Utilization for nonkidney, nonliver organs decreased substantially for all nonstandard donors, however defined. Overall, in 2017, liver was the main organ utilized from older and KDPI >85 donors, while kidney was the main organ utilized from DCD donors.

3.2 | Cost function estimates

We excluded data from four OPOs that were gross outliers (19 datapoints, see Supplemental S2 for description and rationale of outliers) and 25 OPO-years where organ and tissue counts were corrupted, resulting in 194 datapoints, or OPO-years, from 47 OPOs from 2013 through 2017. Table 3 depicts the distribution of cost, production output, and adjustment variables among these 194 OPO-years. From 2013 through 2017, the median OPO had an annual cost of $24 million US dollars and produced 301 kidneys, 306 nonkidney organs, and 710 tissues from 150 deceased donors. Table 4 depicts the main cost function output. Because the total cost is log-transformed, estimates are interpreted as a percent increase. For instance, when the estimate for year is 0.043, it means that the cost in 1 year is $e^{0.043}$, or 104%, that of the previous year (i.e., a 4% increase). A positive estimate suggests that the cost is increasing, whereas a negative estimate suggests that the cost is decreasing. Due to the presence of squared and interaction

TABLE 2 Donor yield, that is, the number of transplants facilitated per deceased donor, by donor type, in 2017

	Standard deceased donor	Nonstandard deceased donor	*p* value
Meeting any definition below			
Number of donors	6642	3649	
Median number of transplants facilitated per donor	3 (3–4)	2 (1–2)	<.0001
Number of single-organ donors	608 (9%)	1098 (30%)	<.0001
Single kidney	95 (1%)	246 (7%)	
Single liver	443 (7%)	803 (22%)	
Single other organ	70 (1%)	49 (1%)	
Number of donors who facilitated:			
Kidney transplant			<.0001
2 transplants	5091 (77%)	1719 (47%)	
1 transplant	684 (10%)	536 (15%)	
Liver transplant	5715 (86%)	1916 (53%)	<.0001
Other organ transplants	4018 (60%)	394 (11%)	<.0001
Definition #1: Donor age <60 versus ≥60			
Number of donors	9003	1288	
Median number of transplants facilitated per donor	3 (2–4)	1 (1–2)	
Number of single-organ donors	1126 (13%)	580 (45%)	<.0001
Single kidney	298 (3%)	43 (3%)	
Single liver	717 (8%)	529 (41%)	
Single other organ	111 (1%)	8 (1%)	
Number of donors who facilitated:			
Kidney transplant			<.0001
2 transplants	6472 (72%)	338 (26%)	
1 transplant	1020 (11%)	200 (16%)	
Liver transplant	6665 (74%)	966 (75%)	.4
Other organ transplants	4290 (48%)	122 (9%)	<.0001
Definition #2: KDPI ≤85 versus KDPI >85 donor			
Number of donors	8629 (84%)	1662 (16%)	
Median number of transplants facilitated per donor	3 (2–4)	1 (1–2)	
Number of single-organ donors	897 (10%)	809 (49%)	<.0001
Single kidney	279 (3%)	62 (4%)	
Single liver	543 (6%)	703 (42%)	
Single other organ	75 (1%)	44 (3%)	
Number of donors who facilitated:			
Kidney transplant			<.0001
2 transplants	6506 (75%)	304 (18%)	
1 transplant	941 (11%)	279 (17%)	
Liver transplant	6430 (75%)	1201 (72%)	.05
Other organ transplants	4158 (48%)	254 (15%)	<.0001
Definition #3: Donation after brain death versus after cardiac death			
Number of donors	8408 (82%)	1883 (18%)	
Median number of transplants facilitated	3 (2–4)	2 (1–2)	
Number of single-organ donors	1431 (17%)	275 (15%)	<.0001
Single kidney	135 (2%)	206 (11%)	
Single liver	1188 (14%)	58 (3%)	

(Continues)

TABLE 2 (Continued)

	Standard deceased donor	Nonstandard deceased donor	*p* value
Single other organ	108 (1%)	11 (1%)	
Number of donors who facilitated:			
Kidney transplant			<.0001
2 transplants	5509 (66%)	1301 (69%)	
1 transplant	963 (11%)	257 (14%)	
Liver transplant	7114 (85%)	517 (27%)	<.0001
Other organ transplants	4299 (51%)	113 (6%)	<.0001

Abbreviation: KDPI, Kidney Donor Profile Index.
Number of transplants facilitated is reported as median (interquartile range).

TABLE 3 Baseline characteristics among 194 organ procurement organization (OPO) years (47 OPOs, 2013–2017)

Variable	Median (interquartile range)	Minimum	Maximum
Dependent/outcome variable			
Total cost	$24,423,395 (13,265,875–38,674,064)	$5,205,609	$84,275,616
Production outputs			
Donor count	150 (74–235)	32	565
Kidney count	301 (158–450)	62	1168
Nonkidney organ count	306 (142–487)	34	2428
Tissue count[a]	710 (10–2188)	0	4922
Eligible death count	159 (83–243)	34	576
Adjustment variables			
Price index	150 (142–171)	124	239
% Donation after cardiac death	16% (10% to 22%)	0%	37%
% Donors age ≥65	6% (3% to 9%)	0%	20%
% Donors with stroke as cause of death	29% (24% to 34%)	14%	61%
% Non-white donor	28% (18% to 47%)	9%	100%

The unit of each variable is per-OPO per year: for instance, the median total cost per-OPO per year (Row 1) is $24 million.
[a]Tissue count includes cornea, skin, and bone grafts.

terms, the estimates for donor and kidney numbers cannot easily be interpreted directly (see Data S1).

3.3 | Cost function projections

We made our projections in 2017 dollars, assuming a price index of 150 (median). Based on Table 2, we assumed that nonstandard donors yielded only kidneys and livers, a conservative assumption that accorded with empiric data on organ usage. Figure 3 illustrates the increased efficiency in procuring more organs per donor: for the median OPO, procuring *one* kidney only from a donor or procuring both kidneys from a donor for *one* double/*en bloc* transplantation results in a marginal cost of $55 k (95% CI $28 k, $99 k), and procuring only the liver (no kidneys) from a donor results in a marginal cost of $41 k (95% CI $12 k, 69 k). Procuring two kidneys from a donor

TABLE 4 Cost function output

Cost function term	Multivariate model with all variables: Estimate	95% confidence interval	Final multivariate model[a]: Estimate	% Increase	95% confidence interval	p value
Intercept	−84.61	−113.57, −55.65	−72.18	—	−100.37, −43.98	<.0001
Production output (all counts are in 100 s)						
Donor count	0.53	0.14, 0.81	0.54	na[b]	0.24, 0.85	.0004
Donor count: square term	−0.083	−0.147, −0.192	−0.098	na[b]	−0.17, −0.028	.006
Kidney count	0.11	−0.021, 0.24	0.10	na[b]	−0.04, 0.24	.2
Kidney count × donor count	−0.048	−0.092, −0.0023	−0.048	na[b]	−0.099, 0.0030	.07
Kidney count × donor count: square term	0.0081	0.0035, 0.013	0.0090	na[b]	0.0034, 0.015	.002
Nonkidney organ count	0.0037	−0.0005, 0.0080	0.0035	0.4%	−0.0009, 0.008	.1
Tissue count	−0.0019	−0.0030, −0.0007	−0.0017	−0.2%	−0.0030, −0.0004	.009
Eligible death count	−0.0003	−0.0012, 0.0000	—	—	—	—
Adjustment variables						
Year (per 1-year increase)	0.049	0.035, 0.064	0.043	+4%	0.0071, 0.029	<.0001
Price index (per 1-point increase)	0.0079	0.0073, 0.035	0.0079	+0.8%	0.0017, 0.014	.01
% Donation after cardiac death	−0.0020	−0.0045, 0.0005	—	—	—	—
% Donors age ≥65	0.0039	−0.0009, 0.0088	—	—	—	—
% Donors with stroke as cause of death	−0.0002	−0.0022, 0.0018	—	—	—	—
% Non-white donor	−0.0001	−0.0009, 0.0030	—	—	—	—

Note: Dependent variable is the natural log of the total cost. % increase refers to the *x*-fold change in the total cost: for instance, for every increase in year, the total cost increases by 4%.

[a]Final multivariate model: only includes the terms for which $p < .1$ in the multivariate model with all variables (left two columns).

[b]na: unable to provide the % increase for these terms, due to the presence of the interaction terms. Please see main results for final projections based on these estimates.

for *two* kidney transplants lowers the marginal cost to $36 k (95% CI $22 k, $66 k) per organ, and procuring two kidneys and a liver for three total transplants further lowers the marginal cost to $24 k per organ (95% CI $17 k, $45 k). A further illustration of the economies of scale is our examination of marginal costs per organ at three levels of production output: 25th percentile, median, and 75th percentile. The cost generally decreases as we move from lower to higher output OPOs, suggesting economies of scale (Figure 3).

4 | DISCUSSION

In these analyses, we applied the multiple-output cost function, a well-validated approach in health economics, to a database based on the CMS-mandated OPO cost reports, which likely forms the most reliable available data on the question in the United States. Our primary goal was to make projections on the incremental cost of kidneys procured from currently underutilized, nonstandard donors. Such an examination is timely and critical, as the transplant community moves toward the laudable goal of increasing deceased donor organ usage. The advantage of the cost function approach is its ability to make projections while remaining agnostic with respect to the details of accounting. We use insights from an examination of organ yield using SRTR data to inform our modeling and projections.

An important insight from our examination of organ utilization is that different organs are underutilized on different donor standards. For instance, older and higher KDPI livers are utilized almost at the same rate as their younger and lower KDPI counterparts, but DCD livers are substantially underutilized compared to non-DCD livers (27% vs. 85%). The reverse is observed for kidneys. We suspect this belies a difference in clinical practice patterns between liver and kidney transplantation: (1) the consequence of primary nonfunction, a fear regarding using DCD organs, is dire in liver transplant, where the recipient is functionally anhepatic and needs an emergent retransplant, and much less so in kidney transplant, where the recipient can wait on dialysis for the next transplant; (2) owing to the availability of dialysis, transplant programs perceive that kidney transplant candidates can wait for a younger or lower KDPI kidney likely to last longer, while liver transplant candidates have a higher waitlist mortality and frequently cannot afford to wait. Such a difference in donor acceptance criteria across different organs leads to more

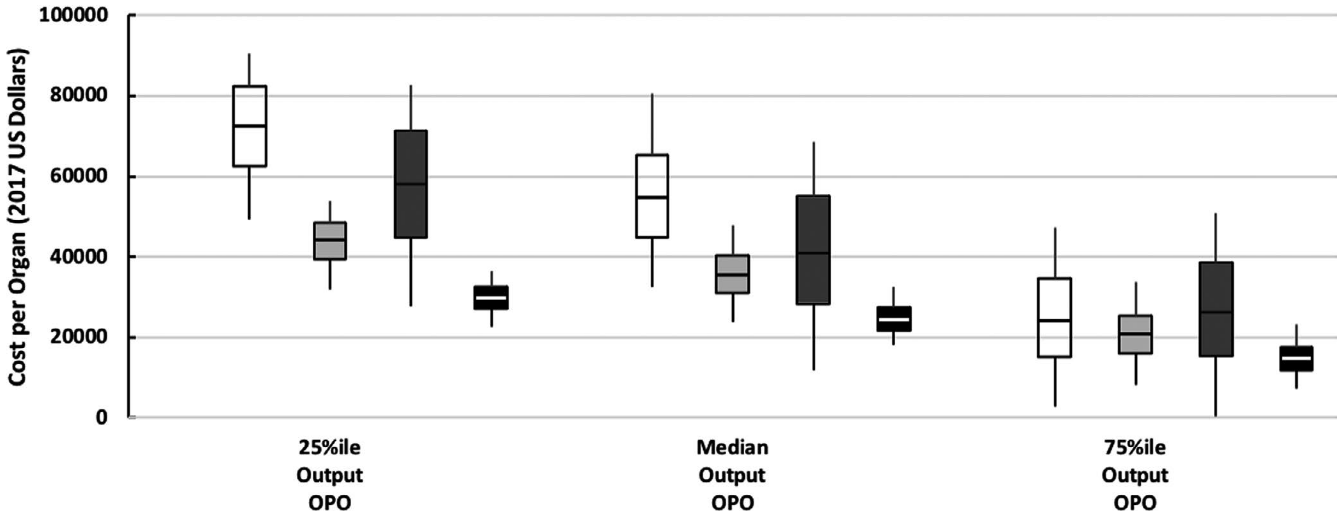

FIGURE 3 Marginal cost per organ, depending on how many transplants are effectuated by the donor. White: one kidney transplant per donor (one or two kidneys transplanted into one recipient); light gray: two kidneys per donor; dark gray: one liver per donor; and black: two kidneys plus one liver transplant per donor. Boxes represent the interquartile range, and whiskers represent the 90% confidence interval

single-organ donors among nonstandard donors and underlies the importance of our study.

Our main finding is that, even in the most expensive scenario, where one deceased donor results in only one patient with kidney failure transplanted (either one kidney is placed or both kidneys are allocated to the same patient), the marginal cost of such a kidney is \$55 k (95% CI \$28 k, \$99 k) for the median OPO that procures 301 kidneys per year. As we would expect, the marginal cost is higher than the *average* OPO cost of a kidney across a broad spectrum of donor yields and donor qualities, which we previously estimated at \$36 k.[14]

Marginal cost is typically lower than average cost, both because of the fixed cost (which is only reflected in the average cost but not in the marginal cost) and because of economies of scale. The higher marginal cost per each additional organ in our model appropriately reflects the higher cost of a single-organ donor procurement. Economies of scale are apparent, both in the shape of the cost curve (Figure 2) and in our projections, showing that costs are lower in higher volume OPOs (Figure 3).

Two other studies have examined the OPO costs of nonstandard donors and both yielded lower estimates (\$8 k[11] and \$15 k[12]). The estimate of \$8 k was from the early 1990 s, nearly 30 years ago. The estimate of \$15 k only accounted for direct costs of "transportation, operation room supplies, investigations, and hospital fees" and did not account for indirect costs.[12] Furthermore, the specific OPO had an associated organ recovery facility, which reduces direct cost by 51%.[18] We hold our estimate to be more representative of what would happen on a national level with a system-wide shift toward more inclusive pursuit of organs.

A notable limitation to our model is the inability to estimate the cost of would-be donors who never became donors. For instance, would-be brain-dead donors may experience clinical deteriorations and expire before organ donation can occur, but the OPO would be responsible for all hospital costs incurred after brain death. DCD donors may also not advance to donation after life support has been withdrawn; the OPO would not be responsible for hospital costs up until then but would be responsible for the cost of donor work-up. Indeed, Lindemann et al.[12] have demonstrated that 115 of 264 (44%) would-be DCD donors incurred the cost of evaluation but did not result in any organs procured. In our current model, this cost of would-be donors is hidden in the large *y* intercept in our model (\$5 million, almost 50% of total cost in the base model). We attempted to use an indirect proxy of these would-be donors—the number of eligible deaths in each OPO jurisdiction; however, adding that to the model neither enhanced model fit nor modified the value of the *y* intercept. It is probable that were OPOs to begin pursuing single-organ donors more enthusiastically, the number of would-be donors will also increase, thereby adding to the marginal cost of each organ in ways not accounted for in our model. This represents an important limitation to our projections.

The other part of the large *y* intercept is the OPO overhead, which is fixed regardless of how many donors and organs result (see Figures 1 and 2). We would expect that operating a fully functional, around-the-clock system for identifying and screening donors, consenting donor families, coordinating donor work-up and procurement, and organ transportation entails a large fixed cost, both in terms of capital and operations. Some surplus capacity is also desirable, given the unpredictable nature of donor availability and the immense value of each organ. Large increases in production frequently necessitate expansion of the overhead as well. For instance, an OPO that wants to increase production from 300 to 400 kidneys a year, for instance, may retain the same overhead (*y* intercept), but an OPO that wants to increase production from 10 to 500 kidneys will need to expand its overhead (e.g., facilities including operating rooms and personnel) substantially and what we think of as the fixed cost/*y* intercept will increase. As most of our projections are for the median-sized OPO, the shift in overhead is likely already factored into the *y* intercept. However, extrapolation to very small or very large OPOs will need to be undertaken with caution.

Whether the higher cost of kidneys from single-organ donors challenge our current notions regarding the cost-effectiveness of using such kidneys depends on the cost of the alternative treatment. In 2017, patients on hemodialysis and peritoneal dialysis incurred \$92 k and \$78 k per person per year (Medicare cost only), compared to \$36 k (Medicare cost only) incurred by transplant recipients.[19] Two cost-effectiveness analyses related to recipients from the contemporary era have been published: Axelrod et al. suggested that transplants using high-KDPI donors are cost effective but not cost saving,[20] and Snyder et al. concluded that waitlist management strategies incorporating DCD are cost effective.[21] Neither study appears to account for potential increases in OPO costs. If we adjusted the total cost (to the entire health care system) of a high-KDPI transplant as estimated by Axelrod et al. (\$331 k) upward by \$55 k, our estimate of the OPO cost of a single-donor kidney, we would arrive at a mean cost of \$386 k over 10 years per high-KDPI transplant, resulting in an average cost per quality-adjusted life-year (QALY) of \$74 k, as compared to the estimated average cost/QALY of Axelrod et al. of \$63 k. The incremental cost-effective ratio of a high-KDPI transplant as compared to dialysis would be \$80 k, rendering the practice still cost effective at usual willingness-to-pay thresholds.[22] Therefore, even allowing for the higher marginal cost of an additional single-donor kidney, using these kidneys remains cost effective at usual willingness-to-pay thresholds, under best available contemporary data. The marginal cost of an additional kidney would need to exceed \$190 k to render a transplant non-cost effective compared to dialysis, at a willingness-to-pay threshold of \$200 000 per QALY.[22] Our model shows that nearly all scenarios across a wide range of donor yields and OPO outputs would yield marginal costs below \$190 k. These projections are an incomplete, crude update on the impact of increased organ costs on the overall cost-effectiveness of transplantation. We have likely underestimated the costs of a nonstandard donor, given inability to account for cost of donation failures as discussed above. Future work should be directed toward understanding how donation failure rates change with donor selection practices and identifying practices to reduce donation failure. Such work could lead to an updated cost-effectiveness analysis examining the economic viability of transplantation.

Our findings have implications for transplant program finances. OPOs charge transplant programs for each organ they utilize by levying a standard acquisition cost (SAC). OPOs set the amount of the SAC to roughly the average cost per organ that year at the OPO level, based on OPO accounting rules. We find that expanding deceased donor utilization will increase the marginal cost of each organ; the increased marginal cost will translate to increased average cost and therefore increased SAC charged to transplant programs. Transplant programs pay the SAC through two avenues: (1) a negotiated rate with private insurers, for recipients who have private insurance, and (2) passing a portion of SAC to Medicare as a part of the Organ Acquisition Cost Center (OACC), depending on what proportion of their recipients have Medicare as their primary insurer.[23] If an OPO increases its SAC as a result of broader organ utilization, a transplant program has to renegotiate rates with the private insurer and/or increase its proportion of Medicare-primary patients in order to maintain fiscal viability. In extreme situations, one can imagine transplant programs turning down organs from more expensive OPOs due to financial pressures, which in turn places pressure on OPOs to alter their practice, including foregoing organs from single-organ donors, to reduce their SAC. Educating payers on the tremendous value of organ transplantation, even in the face of higher price tags, is therefore key to aligning incentives for OPOs and transplant programs with that of patients awaiting transplantation.

In summary, we present an estimate for the procurement costs of kidneys depending on the donor yield. As the transplant community increasingly utilizes nonstandard donors, the organ yield per donor will likely decrease, resulting an increase in the marginal cost, and therefore average cost, of the resulting organs. At \$55 k, even the most expensive scenario, a deceased organ donor facilitating only one kidney transplant, would result in a cost-effective intervention relative to peritoneal or hemodialysis. Expanding organ acceptance criteria represents a laudable goal for the transplant community, although the increase in costs (while still cost effective, owing to markedly superior outcomes with kidney transplantation) need to be acknowledged and accounted for in policy and budgetary decisions.

ACKNOWLEDGMENT

Research here is supported by the John Sobrato Foundation (JCT).

DISCLOSURE

The authors of this manuscript have no conflicts of interest to disclose as described by the *American Journal of Transplantation*.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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REFERENCES

1. McCormick F, Held PJ, Chertow GM. The terrible toll of the kidney shortage. *J Am Soc Nephrol*. 2018;29(12):2775-2776.
2. Summers DM, Watson CJE, Pettigrew GJ, et al. Kidney donation after circulatory death (DCD): state of the art. *Kidney Int*. 2015;88(2):241-249.
3. Perez-Saez M, Arcos E, Comas J, Crespo M, Lloveras J, Pascual J. Survival benefit from kidney transplantation using kidneys from deceased donors aged ≥75 years: a time-dependent analysis. *Am J Transplant*. 2016;16(9):2724-2733.
4. Aubert O, Reese PP, Audry B, et al. Disparities in acceptance of deceased donor kidneys between the United States and France and estimated effects of increased US acceptance. *JAMA Intern Med*. 2019;179(10):1365-1374.
5. Hart A, Smith JM, Skeans MA, et al. Annual data report: kidney. *Am J Transplant*. 2018;20(S1):20-130.

6. Feng S, Lai JC. Expanded criteria donors. *Clin Liver Dis*. 2014;18(3):633-649.
7. Beaupre RA, Morgan JA. Donation after cardiac death: a necessary expansion for heart transplantation. *Semin Thorac Cardiovasc Surg*. 2019;31(4):721-725.
8. Dziodzio T, Jara M, Hardt J, et al. Effects of expanded allocation programmes and organ and recipient quality metrics on transplant-related costs in kidney transplantation - an institutional analysis. *Transpl Int*. 2019;32(10):1074-1084.
9. Axelrod DA, Schnitzler MA, Xiao H, et al. The changing financial landscape of renal transplant practice: a national cohort analysis. *Am J Transplant*. 2017;17(2):377-389.
10. Englesbe MJ, Ads Y, Cohn JA, et al. The effects of donor and recipient practices on transplant center finances. *Am J Transplant*. 2008;8:586-592.
11. Jacobbi LM, McBride VA, Etheredge EE, et al. The risks, benefits, and costs of expanding donor criteria: A collaborative prospective three-year study. *Transplantation*. 1995;60(12):1491-1496.
12. Lindemann J, Dageforde LA, Vachharajani N, et al. Cost evaluation of a donation after cardiac death program: How cost per organ compares to other donor types. *J Am Coll Surg*. 2018;226(5):909-916.
13. Remuzzi G, Grinyo J, Ruggenenti P, et al. Early experience with dual kidney transplant in adults using expanded donor criteria. Double Kidney Transplant Group (DKG). *J Am Soc Nephrol*. 1999;10(12):2591-2598.
14. Held PJ, Bragg-Gresham JL, Peters T, Chertow GM, McCormick F, Roberts JP. The cost of procuring deceased donor kidneys: Evidence from the OPO cost reports 2013-2017. *Am J Transplant*. 20(4):1087-1094.
15. Grannemann TW, Brown RS, Pauly MV. Estimating hospital costs: a multiple-output analysis. *J Health Econ*. 1986;5:107-127.
16. Dor A. The costs of Medicare patients in nursing homes in the United States. *J Health Econ*. 1989;1989:253-270.
17. Dor A, Held PJ, Pauly MV. The Medicare cost of renal dialysis: evidence from a statistical cost function. *Med Care*. 1992;30(10):879-891.
18. Doyle M, Subramanian V, Vachharajani N, et al. Organ donor recovery performed at an organ procurement organization-based facility is an effective way to minimize organ recovery costs and increase organ yield. *J Am Coll Surg*. 2016;222(4):591-600.
19. United States Renal Data System. *2019 USRDS Annual Data Report: Epidemiology of Kidney Disease in the United States*. Bethesda, MD: National Institutes of Health, National Institute of Diabetes and Digestive and Kidney Diseases National Institute of Diabetes and Digestive and Kidney Diseases; 2019.
20. Axelrod DA, Schnitzler MA, Xiao H, et al. An economic assessment of contemporary kidney transplant practice. *Am J Transplant*. 2018;18:1168-1176.
21. Snyder RA, Moore DR, Moore DE. More donors or more delayed graft function? A cost-effectiveness analysis of DCD kidney transplantation. *Clin Transplant*. 2013;27(2):289-296.
22. Ryen L, Svensson M. The willingness to pay for a quality adjusted life year: a review of the empirical literature. *Health Econ*. 2015;24:1289-1301.
23. Abecassis M. Organ acquisition cost centers part I: medicare regulations-truth or consequence. *Am J Transplant*. 2006;6:2830-2835.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Cheng XS, Held PJ, Dor A, et al. The organ procurement costs of expanding deceased donor organ acceptance criteria: Evidence from a cost function model. *Am J Transplant*. 2021;21:3694–3703. https://doi.org/10.1111/ajt.16617