Association of Center Volume with Outcome After Liver and Kidney Transplantation

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Outcomes for certain surgical procedures have been linked with volume: hospitals performing a high number of procedures demonstrate better outcomes than do low-volume centers. This study examines the effect of volume on hepatic and renal transplant outcomes. Data from the Scientific Registry of Transplant Recipients were analyzed for transplants performed from 1996–2000. Transplant centers were assigned to volume quartiles (kidney) or terciles (liver). Logistic regression models, adjusted for clinical characteristics and transplant center clustering, demonstrate the effect of transplant center volume quantile on 1-year post-transplant patient mortality (liver) and graft loss (kidney). The unadjusted rate of renal graft loss within 1 year was significantly lower at high volume centers (8.6%) compared with very low (9.6%), low (9.9%) and medium (9.7%) volume centers (p = 0.0014). After adjustment, kidney transplant at very low [adjusted odds ratio (AOR) 1.22; p = 0.043) and low volume (AOR 1.22 p = 0.041) centers was associated with a higher incidence of graft loss when compared with high volume centers. Unadjusted 1-year mortality rates for liver transplant were significantly different at high (15.9%) vs. low (16.9%) or medium (14.7%) volume centers. After adjustment, low volume centers were associated with a significantly higher risk of death (AOR 1.30; p = 0.0036). There is considerable variability in the range of failure between quantiles after kidney and liver transplant. Transplant outcomes are better at high volume centers; however, there is no clear minimal threshold volume.

Key words: Graft failure, kidney transplantation, liver transplantation, medical center, mortality, outcomes, SRTR, volume

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Introduction

Over the last two decades, a strong relationship has been reported between higher volume, defined as the number of cases of a given procedure performed at a hospital, and decreased morbidity and mortality following complex surgical procedures (1,2). This effect likely reflects a combination of better surgical technique, higher quality perioperative care, and the increase in referral volume that results from a history of good outcomes. Furthermore, the beneficial effect of volume extends beyond the early postoperative period; improved long-term outcomes at high-volume centers have been demonstrated for surgical treatment of pancreatic cancer (3) and pulmonary resections (4).

Organ transplantation outcomes reflect the influence of many factors: patient and donor selection, case mix, timeliness of donor availability, operative technique, and postoperative medical management and immunosuppression. While several previous studies have reported that outcomes at higher volume centers are better following pediatric renal (5), cardiac (6), and liver transplantation (7), others have failed to demonstrate this effect (8). The present study examines the effect of center volume on renal and hepatic transplant outcomes using risk-stratified models of national data for all patients undergoing these two transplant procedures over a recent 5-year period.

Methods

Data from the Scientific Registry of Transplant Recipients (SRTR) were analyzed for all adult patients who underwent hepatic or renal transplantation from January 1, 1996 to December 31, 2000. The primary outcome was death at 1 year (liver) and graft failure including death with a functioning graft at 1 year (kidney). Models were adjusted for the following covariates: donor characteristics [age, race, cause of death, gender, expanded criteria donor status (9) (kidney), living or deceased donor source], recipient characteristics [age, race, gender, previous organ transplant, preoperative hospitalization, panel reactive antibody (PRA) level (kidney), use of induction therapy with antilymphocyte antibodies (kidney), HLA mismatching (kidney), time on dialysis before transplant (kidney)], elevated creatinine (liver), and cold ischemia time.

Total transplant center volume over the study period for the organ of interest was used to assign each center into a volume quantile. Renal transplant centers were divided a priori into quartiles consisting of an equivalent number of transplants (the number of transplant centers varies between quartiles). Liver transplant centers were assigned to volume terciles. Volume cut-off points, including the number of quantiles, were selected before outcome data analysis to avoid bias. The use of terciles rather than quartiles for the liver model reflects the lower number of such procedures and was chosen to enhance statistical stability. Patients with at least 1 year of follow up were included in all subsequent analyses.

Descriptive statistics were compiled and analyzed to assess the relationship between the available covariates and the outcomes of interest, using the Student's *t*-test and Chi-square analyses, as appropriate. Covariates associated with mortality or graft failure (p < 0.10) were included in multivariate logistic regression analyses. Endpoints for the logistic regression models were death at 1 year (liver) and graft failure or death at 1 year (kidney). Volume quantiles were included as a series of categorical variables, with the highest volume quantile as the reference group. For the logistic regression models, generalized estimating equations were used to account for clustering at the transplant center level, assuming a compound symmetry covariance structure (10). This method accounts for the fact that patients within a transplant center may be more similar to each other than to patients in other transplant centers owing to center-specific physician and treatment practices.

Statistical analyses were conducted using SAS 8.0 (10). The project was approved by the University of Michigan Medical School Institutional Review Board.

Results

Kidney transplant center, donor, and recipient characteristics

Between 1996 and 2000, 60 778 kidney transplants were performed at 258 US transplant centers. Transplant center volume varied widely (Table 1). The very low-volume quartile centers performed 1–45 transplants per year (median 20, n = 15 127). Low-volume quartile centers performed 46–75 transplants per year (median 58, n = 15 084). Medium-volume quartile centers performed 76–124 transplants annually (median 93, n = 15 169), while high-volume quartile centers performed 125–278 transplants yearly (median 167, n = 15 398).

Recipient characteristics varied significantly between volume quartiles (Table 2). Centers in the very low-volume quartile had a significantly lower proportion of 35–49-year-old recipients than did centers in the high-volume quartile (36.1% vs. 37.0%; p < 0.001). Very low-volume centers also had a lower proportion of patients older than 64 years when compared with high-volume centers (7.4% vs. 8.1%; p < 0.001).

Donor characteristics (living and deceased combined) also varied across volume quartiles (Table 3). Very low-volume

Table 1: Kidney transplant center characteristics by volume quartile

	Volume quartile				
	Very low	Low	Medium	Large	p-value
Number of renal transplants (1996–2000)	15 127	15 084	15 169	15 398	
Number of centers	158	51	32	17	
Median annual volume per center	20	58	93	167	
Unadjusted graft failure rate at 1 year (%)	9.6	9.9	9.7	8.6	0.0014

Table 2: Kidney transplant recipient characteristics by volume quartile

	Volume quartile				
	Very low	Low	Medium	Large	p-value
Age 18–34 (%)	23.1	22.4	21.4	21.2	<0.001
Age 35–49 (%)	36.1	38.1	36.5	37.0	<0.001
Age 50–64 (%)	33.4	32.8	33.7	33.7	<0.001
Age > 64 (%)	7.4	6.8	8.4	8.1	<0.001
Female (%)	40.0	41.3	41.0	39.5	0.0056
African-American race (%)	20.7	26.1	25.0	20.5	<0.001
Asian race (%)	4.3	3.0	4.1	4.9	<0.001
PRA 80–100 (%)	6.7	7.5	5.9	6.5	<0.001
Diabetic nephropathy (%)	22.5	21.2	20.1	21.5	<0.001
Hypertension (%)	13.1	16.0	14.7	14.8	<0.001
Tubular/interstitial (%)	6.2	6.1	6.2	5.5	0.0543
Polycystic kidney disease (%)	8.6	8.4	9.6	8.5	0.0009
Vascular disease (%)	5.2	4.6	5.5	4.2	<0.001
Congenital abnormality (%)	1.9	1.6	1.7	1.3	0.0032
Previous kidney transplant (%)	11.2	12.1	12.2	11.8	0.0404
Use of induction therapy (%)	45.3	35.7	32.6	43.4	<0.001
Mean time on dialysis (years) before transplant	3.3	3.5	3.4	3.4	<0.001

Table 3: Kidney donor characteristics by volume quartile

	Volume quartile				
	Very low	Low	Medium	Large	p-value
Donor < 18 (%)	12.2	11.2	11.3	11.2	<0.001
Donor 18–34 (%)	31.5	30.7	28.1	29.6	<0.001
Donor 35–49 (%)	34.5	35.1	36.3	34.5	<0.001
Donor 50–64 (%)	19.2	19.9	20.9	21.5	<0.001
Donor > 64 (%)	2.6	3.1	3.4	3.1	<0.001
African-American race (%)	9.8	13.1	12.6	10.6	<0.001
Living donor (%)	32.3	36.7	33.9	35.8	<0.001
Expanded criteria donor (%)	9.3	9.4	10.8	10.2	<0.001
Mean cold ischemia time (h) for deceased donors	18.5	20.5	21.4	22.1	<0.001

centers were significantly less likely to use kidneys from donors who were older than 64 years and were significantly more likely to use organs from donors younger than age 35 years when compared with high-volume centers (p < 0.001). The percentage of transplants using organs from living donors also varied significantly across volume quartiles: 32.3% of transplants involved living donors in very low-volume centers, 36.7% in low-volume centers, 33.9% in medium-volume centers, and 35.8% in high-volume centers (p < 0.001). Cold ischemia time increased with volume. Among deceased donors, the mean cold ischemia time was 18.5 h in very low-volume centers and 22.1 h in high-volume centers (p < 0.001).

One-year kidney transplant graft outcomes
The overall 1-year unadjusted kidney graft failure rate was 9.4%, and the rates varied significantly by volume quartile (Table 1). The unadjusted rate of graft failure was lowest in the high-volume quartile centers (8.6%) and higher in the very low (9.6%), low (9.9%), and medium (9.7%) volume centers (p = 0.0014).

Multivariate logistic regression models of graft failure were fitted to adjust for the observed differences in donor, recipient, and transplant characteristics across volume quartiles (Table 4). A significantly higher odds ratio of graft failure at 1 year was found in association with older recipient age, African-American recipient race, high PRA, diabetes, hypertension, tubular diseases, vascular nephropathy, preoperative intensive care requirements, older donor age, African-American donor race, longer cold ischemia time, increased number of HLA mismatches, increased time on dialysis before transplant, and expanded criteria donor kidney. Several factors were found to be associated with significantly lower odds of 1-year graft failure, including receipt of a living donor organ, donor age 18–34 years, recipient Asian race, and recipient diagnosis of polycystic kidney disease. In this analysis, transplants at very low-volume centers [adjusted odds ratio (AOR) 1.22; p = 0.043], low-volume centers (AOR 1.22; p = 0.041), and medium-volume centers (AOR 1.21; p = 0.061) were associated with significantly increased odds of graft failure at 1 year, when compared

with high-volume centers, adjusted for all other factors. The 95% confidence intervals for odds of graft failure for patients at very low-, low-, and medium-volume centers overlapped each other. Corresponding predicted probabilities of graft failure at 1 year for the average kidney recipient were 8.7%, 8.7%, 8.7%, and 7.2%, respectively. In separate analyses, differences between volume quartiles were also shown to be significant within the first 30 days after transplant (Table 5), suggesting that the majority of the center volume effect is seen within the first post-transplant month.

While the average risk of graft failure was significantly higher for transplants performed at very low- and low-volume quartile centers, all four quartiles had substantial variability in their estimated within-quartile risk (Figure 1A). This suggests that the outcome at any given center within the very low- or low-volume quartile is not necessarily worse than that at a high-volume center.

Liver transplant center, donor, and recipient characteristics
Between 1996 and 2000, 19 084 adult liver transplants were performed in the United States at 111 centers (Table 6). Median annual liver transplant center volume varied markedly across the volume terciles. In the lowest volume tercile, 74 centers performed 6258 transplants (median annual volume 21 [range 1–37]). In the medium-volume tercile, 25 centers performed 6270 transplants (median annual volume 48 [range 39–66]). At the 12 centers in the high-volume tercile, 6556 transplants were performed (median annual volume 93 [range 66–176]).

Liver transplant recipient characteristics demonstrated significant differences across volume terciles (Table 7). Older patients (>64 years) constituted 10.4% of recipients at high-volume centers but only 6.0% at low-volume centers (p < 0.001). Compared with the high-volume tercile, patients at low-volume tercile centers were less likely to be Asian (2.9% vs. 4.5% p < 0.001) and more likely to be African-American (8.2% vs. 6.6% p = 0.0017). Patients at high-volume tercile centers were significantly more likely

Table 4: Factors associated with kidney allograft failure at 1 year

	Adjusted odds ratio	95% confidence interval		p-value
Very low-volume transplant center	1.22	1.01	1.48	0.043
Low-volume transplant center	1.22	1.01	1.48	0.041
Medium-volume transplant center	1.21	0.99	1.49	0.061
High-volume transplant center	1.00	–	–	Reference
Recipient age 18–34	1.03	0.94	1.12	0.54
Recipient age 35–49	1.00	–	–	Reference
Recipient age 50–64	1.35	1.26	1.45	<0.001
Recipient age > 64	1.79	1.62	1.97	<0.001
Donor age < 18	0.98	0.87	1.09	0.71
Donor age 18–34	0.85	0.78	0.92	<0.001
Donor age 35–49	1.00	–	–	Reference
Donor age 50–64	1.27	1.16	1.39	<0.001
Donor age > 64	1.52	1.30	1.78	<0.001
HLA mismatch	1.10	1.08	1.13	<0.001
Donor African-American	1.26	1.15	1.38	<0.001
In hospital ICU	2.36	1.59	3.51	<0.001
Cold ischemia time (per hour)	1.01	1.00	1.01	<0.001
Previous kidney transplant	1.09	0.97	1.22	0.16
Recipient African-American	1.11	1.02	1.20	0.012
Recipient Asian	0.71	0.60	0.84	0.0001
Living donor	0.69	0.63	0.76	<0.001
PRA < 10%	1.00	–	–	Reference
PRA 10%–80%	1.16	1.08	1.25	<0.001
PRA > 80%	1.48	1.33	1.64	<0.001
Diabetes	1.14	1.05	1.24	0.0021
Hypertension	1.08	0.99	1.19	0.096
Polycystic kidney disease	0.83	0.73	0.93	0.0017
Tubular diseases	1.18	1.04	1.33	0.012
Vascular nephropathy	1.12	0.97	1.29	0.11
Congenital	1.11	0.88	1.39	0.38
Other diagnoses	1.14	1.03	1.25	0.011
Expanded criteria donor	1.33	1.20	1.48	<0.001
Use of induction therapy	1.01	0.95	1.09	0.68
Time on dialysis before transplant (per year)	1.02	1.01	1.03	0.0001

Table 5: Adjusted early (30 days) and conditional (31–365 days) kidney graft loss by center volume quartile

	Adjusted odds ratio at 30 days	95% confidence interval		p-value
Very low-volume transplant center	1.35	1.07	1.70	0.01
Low-volume transplant center	1.35	1.07	1.72	0.01
Medium-volume transplant center	1.28	0.98	1.67	0.07
High-volume transplant center	1.00	–	–	Reference
	Conditional adjusted odds ratio at 31-365 days	95% confidence interval		p-value
Very low-volume transplant center	1.13	0.91	1.40	0.26
Low-volume transplant center	1.12	0.91	1.39	0.29
Medium-volume transplant center	1.14	0.90	1.43	0.27
High-volume transplant center	1.00	–	–	Reference

to have a diagnosis of malignancy than those at low-volume tercile centers (4.6% vs. 2.1%; p < 0.001). Patients at centers in the high-volume tercile appear to have been sicker than those at centers in the medium- or low-volume terciles, as assessed by higher incidences of elevated pre-transplant serum creatinine (p < 0.001), requirement for life support (p = 0.0042), and preoperative intensive care unit requirement (p < 0.001). Finally, a significantly higher proportion of patients at high-volume centers had undergone a previous liver transplant (11.4%) compared with medium-volume centers (8.8%) and low-volume centers (7.5%) (p < 0.001).

Donor characteristics also varied across volume terciles (Table 8). Transplants at high-volume centers utilized organs from a significantly greater proportion of donors older
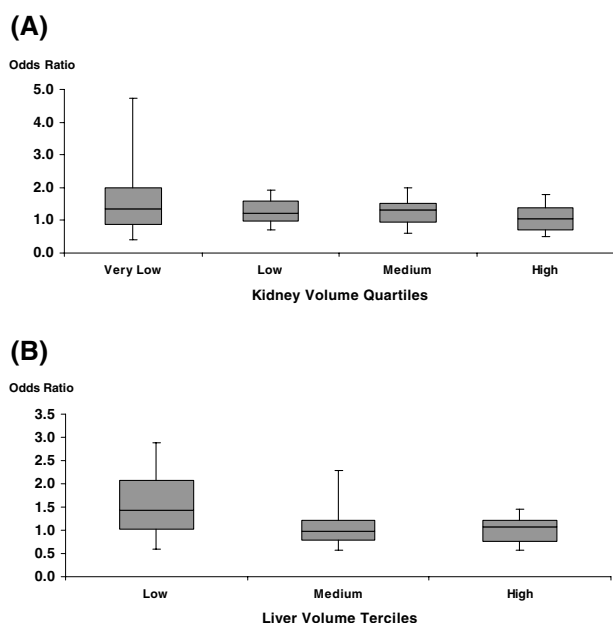
(A)

(B)

Figure 1: (A) Box plot of distribution of adjusted odds ratio of graft failure or death at 1 year after kidney transplant by center within volume quartile. (B) Box plot of distribution of adjusted odds ratio of death at 1 year after liver transplant by center within volume tercile.

than age 64 years than did low-volume centers (10.3% vs. 4.7%; p < 0.001) and were associated with longer mean cold ischemia time than medium-volume centers (8.8 h vs. 8.3 h; p < 0.001). No significant differences were found in the use of living liver donors across volume terciles (p = 0.45).

One-year mortality after liver transplant

Unadjusted 1-year post-transplant mortality rates varied across volume terciles (Table 6). In the high-volume tercile, 1-year mortality was 15.9%. In the medium- and low-volume terciles, mortality rates were 14.7% and 16.9%, respectively. However, after adjustment for recipient, donor, and transplant characteristics, liver transplants at low-volume tercile centers were found to be associated with 30% higher odds of death (AOR 1.30; p = 0.0036) when compared with high-volume centers (Table 9). Although the odds ratio for death at medium-volume centers was very similar to high-volume centers, there was no significant difference between low- and medium-volume centers. Predicted probabilities of death at 1-year for the average liver recipient were 16.5%, 13.7%, and 13.2% for transplants performed at low-, medium-, and high-volume tercile centers, respectively. Other factors associated with significantly higher odds of 1-year mortality included older recipient age, previous organ transplant, preoperative intensive care unit admission, requirement for life support, elevated

Table 6: Liver transplant center characteristics by volume tercile

	Volume tercile			
	Low	Medium	High	p-value
Number of liver transplants (1996–2000)	6258	6270	6556	
Number of centers	74	25	12	
Median annual volume per center	21	48	93	
Unadjusted death rate at 1 year	16.9	14.7	15.9	0.0032

Table 7: Liver recipient characteristics by volume tercile

	Volume tercile			
	Low	Medium	High	p-value
Age 18–34 (%)	7.5	7.6	7.8	<0.001
Age 35–49 (%)	43.9	42.0	37.7	<0.001
Age 50–64 (%)	42.7	43.2	44.1	<0.001
Age > 64 (%)	6.0	7.2	10.4	<0.001
African-American race (%)	8.2	7.3	6.6	0.0017
Asian race (%)	2.9	2.9	4.5	<0.001
Cholestatic liver disease (%)	13.3	13.6	14.0	0.46
Acute hepatic necrosis (%)	8.2	9.2	6.5	<0.001
Metabolic disease (%)	3.2	3.0	3.1	0.73
Malignancy (%)	2.1	2.5	4.6	<0.001
Creatinine > 2.0 (%)	10.9	11.1	13.7	<0.001
ABO incompatible (%)	1.5	1.5	1.3	0.55
On life support (%)	10.2	9.5	11.3	0.0042
In ICU before transplant (%)	22.2	19.0	23.4	<0.001
Previous liver transplant (%)	7.5	8.8	11.4	<0.001

Table 8: Liver donor characteristics by volume tercile

| | Volume tercile | | | |
	Low	Medium	High	p-value
Age < 18 (%)	15.4	15.2	12.2	<0.001
Age 18–34 (%)	33.5	32.0	28.3	<0.001
Age 35–49 (%)	27.8	26.5	26.9	<0.001
Age 50–64 (%)	18.7	20.1	22.2	<0.001
Age > 64 (%)	4.7	6.2	10.3	<0.001
African-American race (%)	11.3	11.2	11.2	0.97
Living donor (%)	2.4	2.4	2.1	0.45
Mean cold ischemia time (h)	8.6	8.3	8.8	<0.001

Table 9: Factors associated with death at 1 year following liver transplant

	Adjusted odds ratio	95% confidence interval		p-value
Low-volume transplant center	1.30	1.09	1.56	0.0036
Medium-volume transplant center	1.05	0.84	1.30	0.68
High-volume transplant center	1.00	–	–	Reference
Recipient age 18–34	0.74	0.62	0.89	0.0018
Recipient age 35–49	1.00	–	–	Reference
Recipient age 50–64	1.28	1.16	1.42	<0.001
Recipient age > 64	1.88	1.62	2.19	<0.001
In hospital ICU	1.24	1.08	1.42	0.0024
On life support	1.58	1.32	1.90	<0.001
Previous liver transplant	2.50	2.21	2.82	<0.001
Cholestatic liver disease/cirrhosis	0.73	0.65	0.84	<0.001
Acute hepatic necrosis	1.12	0.99	1.27	0.077
Metabolic disease	0.89	0.66	1.20	0.46
Malignancy	1.29	1.09	1.53	0.0032
Serum creatinine > 2.0	1.73	1.54	1.93	<0.001
Living Donor	1.59	1.24	2.05	0.0003
Donor age < 18	0.88	0.76	1.02	0.084
Donor age 18–34	0.83	0.75	0.91	0.0002
Donor age 35–49	1.00	–	–	Reference
Donor age 50–64	1.26	1.14	1.38	<0.001
Donor age > 64	1.57	1.36	1.81	<0.001
Donor African-American race	1.24	1.07	1.44	0.0038
Donor Asian race	1.29	0.90	1.86	0.17
Donor or other unknown races	1.12	0.80	1.58	0.51
Cold ischemia time (per hour over >8.25 h)	1.02	1.01	1.03	<0.001

pretransplant serum creatinine, diagnosis of acute hepatic necrosis or malignancy, living donor source, longer cold ischemia time, older donor age, and African-American donor race. Associated with significantly lower 1-year mortality rates were younger recipient age, diagnosis of cholestatic liver disease, and younger donor age.

As in the kidney graft outcome analysis, across the three liver-volume terciles there was substantial overlap in the distribution of estimates of the odds of mortality after liver transplant by center (Figure 1B). Thus, even though outcomes on average were worse at low-volume centers, the outcomes at some low-volume liver transplant centers were comparable to, or in some cases better than, those at some high-volume centers.

Discussion

This study confirms an association between transplant center volume and outcomes following kidney and liver transplantation in a modern cohort of recipients. Using an analysis that included clinical information for risk adjustment, the odds of kidney transplant graft failure at 1 year were 22% higher (p = 0.043) at very low-volume centers, 22% higher (p = 0.041) at low-volume centers, and 21% higher (p = 0.061) at medium-volume centers compared with procedures carried out at high-volume centers. Patients undergoing liver transplants at low-volume centers had 30% (p = 0.0036) higher odds of death at 1 year compared with those who received their allografts at high-volume centers.

These results are consistent with those of Edwards et al. (7) who analyzed liver transplant outcomes, and Schurman et al. (5) who examined the outcomes of pediatric renal transplants. The former analysis looked at liver transplant outcomes from 1987 to 1994; 1-year mortality at centers that performed fewer than 20 transplants per year and were not affiliated with a high-volume center was 28.3% compared with 18.2% at centers that performed more than 20 transplants (OR 2.08; 95% confidence interval 1.65–2.61). However, unlike the current study, there was a significant discrepancy between the total number of transplants performed at high- (89%) and low- (11%) volume centers. In addition, the volume cut-off was determined after a review of data from the previous 5 years, which may have enhanced the differences between the two groups (11). The latter analysis of pediatric renal transplant data from 1987 to 1995 demonstrated a modest effect of volume on kidney graft survival. At centers where more than 100 transplants were performed during the study period, 3-month graft survival was 90.4% compared with 90.2% at centers that performed 50–99 transplants and 88.4% at centers that performed fewer than 50 transplants. These authors showed important volume-related differences in the etiology of graft failure (including graft thrombosis) and the incidence of acute tubular necrosis. They correlated these differences with variation in anti-T-cell antibody use across volume strata.

The volume effects reported in our analysis, while statistically significant, are modest in comparison with the effect size reported in studies of widely performed nontransplant surgical procedures. For example, in studies of the Medicare population, high-volume centers were associated with significantly lower odds of perioperative mortality, ranging from 12% for carotid endarterectomy to 80% for pancreatic resection (1). Several possible explanations may be offered for the modest volume outcome effect size in kidney and liver transplantation. First, unlike the Medicare analysis, the current analysis used clinical data from the SRTR rather than relying upon claims data or other administrative data sources. The ability to perform detailed risk adjustment using clinical data has been reported to reduce the measured effect of volume on outcome in other studies (2). Second, the subset of American hospitals where transplantation is performed is small and select. In general, these hospitals must demonstrate skilled anesthesia, radiology, and intensive care capabilities in order to establish a transplant program (12). Many of the process variables that contribute to volume differences across a more diverse group of hospitals performing less scrutinized and regulated surgical procedures may not vary to the same degree among transplant centers. Third, transplant centers are subject to a legislatively mandated review process, administered by a government contractor, which is designed to ensure high-quality care. Center performance that is significantly worse than expected is flagged for audit, review, and remediation.

This analysis does have several limitations. Despite the rich set of data available from the SRTR, there are clearly additional details that may help explain our findings. For instance, detailed information on the existence of other potentially important comorbid conditions (e.g. coronary artery disease) was not available. However, it appears unlikely that the observed differences are the result of low-volume centers caring for sicker patients compared with high-volume centers. In fact, high-volume kidney and liver transplant centers had higher incidences of older recipients, patients in the intensive care units, and use of organs from older donors.

This analysis does not provide evidence of a threshold that could be used to determine a minimum volume standard for transplant centers. The study design specifically avoided the pitfall of post hoc determinations of center volumes associated with better or worse outcome. Rather, we assigned patients into volume quantiles a priori. This allowed construction of logistic regression models based on equal numbers of patients, rather than equal numbers of centers. The analysis also demonstrates that there is a large amount of overlap in the range of outcomes across volume quantiles.

We did not have detailed process variable information (e.g. operative blood loss) that may have helped to explain better outcomes at high-volume centers. Thus, this analysis is limited in its ability to proffer advice on changing practice at a given center. Also, we did not examine the potential interaction between center volume and other variables. Outcome differences may be concentrated primarily in older patients, as has been shown in coronary artery bypass grafting (13), or among those with previous transplants. However, while these potential interactions may alter the magnitude of the effect among subgroups, they are unlikely to alter the fundamental relationships observed here, as these factors were adjusted for in the multivariate logistic regression models.

Several potential implications arise from the results of this study. Currently, efforts are under way to concentrate surgical procedures with significant volume-outcome effects to large-volume centers (14). The adoption of such a policy for liver and kidney transplantation would not be straightforward even if it were desirable, particularly in the case of deceased donor transplantation. As with HLA matching, the benefit of high-volume center performance must be carefully weighed against the increased risk of graft loss associated with the increased cold ischemia time which would likely accompany increased regionalization of transplant services (15). Furthermore, the frequent follow-up visits necessary after transplantation might prove to be an added hardship if patients were forced to travel great distances. Because patients may be more compliant with follow-up visits if appointments are convenient, compliance may also be an important determinant of outcome.

The data suggest that there is room for quality improvement. If poor outcome is associated with low-volume, then low-volume centers with poor outcomes should be offered assistance in identifying contributing factors. Furthermore, small centers could be affiliated with larger centers to ensure that care plans are maintained at state-of-the-art levels. High-volume centers should be studied in an attempt to identify best practices associated with superior outcome. If identified, these patient selection or management strategies could be promulgated to low-volume centers.

In conclusion, outcomes for patients who receive liver or renal transplants at high-volume centers are better than those among patients who receive these organs at lower-volume transplant centers. Future work should examine process variables that differ between high- and lower-volume centers and examine the interaction of comorbid conditions and center volume. Despite potential advantages of regionalization to large-volume centers, caution is necessary, given the potential adverse effects of increased cold ischemia time and the implications for post-transplant monitoring.

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