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INTRODUCTION

Many deceased-donor kidney transplants (KTs), and even some living-donor KT through paired donation, rely on commercial air transport. Interestingly, a safety study by the Organ Procurement and Transplantation Network (OPTN) showed that 49.4% of transportation failures or near misses were due to cancelled or delayed flights. Therefore, any substantial decrease in commercial airline transportation would be inherently of particular interest to the KT community.

The coronavirus-19 (COVID-19) pandemic has been an extreme example of a supply chain disruption in sectors across the world. In particular, the pandemic has substantially disrupted the commercial airline industry. Due to travel restrictions, “shelter-in-place” governmental

Many deceased-donor and living-donor kidney transplants (KTs) rely on commercial airlines for transport. However, the coronavirus-19 pandemic has drastically impacted the commercial airline industry. To understand potential pandemic-related disruptions in the transportation network of kidneys across the United States, we used national flight data to compare scheduled flights during the pandemic vs 1-year earlier, focusing on Organ Procurement Organization (OPO) pairs between which kidneys historically most likely traveled by direct flight (High Volume by direct Air transport OPO Pairs, HVA-OPs). Across the United States, there were 39% fewer flights in April 2020 vs April 2019. Specific to the kidney transportation network, there were 65.1% fewer flights between HVA-OPs, with considerable OPO-level variation (interquartile range [IQR] 54.7%-75.3%; range 0%-100%). This translated to a drop in median number of flights between HVA-OPs from 112 flights/wk in April 2019 to 34 in April 2020 (P < .001), and a rise in wait time between scheduled flights from 1.5 hours in April 2019 (IQR 0.76-3.3) to 4.9 hours in April 2020 (IQR 2.6-11.2; P < .001). Fewer flights and longer wait times can impact logistics as well as cold ischemia time; our findings motivate an exploration of creative approaches to KT transport as the impact of this pandemic on the airline industry evolves.

KEYWORDS
clinical research/practice, kidney disease, kidney transplantation/nephrology, quality of care/care delivery
organ transportation in the United States. Organizations (OPOs), and to ensure the continued viability of long-distance transport. The lower number of routes and frequencies of flights has the potential to increase logistical complexity, travel times, and cold ischemia time (CIT) in KT. However, the commercial air travel network as used for KT, and changes to the robustness of this network under COVID-19, have not been described.

To address this gap, we quantified the availability and frequency of flights along routes most commonly used for transport of kidneys for transplantation, as well as changes to flight availability under COVID-19, to understand the potential impact of the pandemic on kidney transportation and feasibility of long-distance transport. A novel approach to understanding the air transport network and disruptions due to COVID-19 is critical to forecast the impact of near-future changes of the airline industry on KT going forward, to inform Organ Procurement Organizations (OPOs), and to ensure the continued viability of long-distance transportation of kidneys in the United States.

2 | METHODS

2.1 | Data sources

This study used data from the Scientific Registry of Transplant Recipients (SRTR). The SRTR data system includes data on all donor, waitlisted candidates, and transplant recipients in the United States, submitted by the members of the OPTN. The Health Resources and Services Administration, US Department of Health and Human Services provides oversight to the activities of the OPTN and SRTR contractors. This dataset has previously been described elsewhere. The flight data for this project came from a proprietary database used by cHealthworks Logistics to plan, analyze, and execute organ transportation movements. This database synthesizes the Bureau of Transportation Statistics and the Official Airline Guide databases.

2.2 | Defining the kidney air transportation network in the United States

We studied 10 710 adult and pediatric kidney deceased-donor transplant recipients who underwent KT between January 1, 2018 and March 2, 2019, and whose donor kidney originated in a different OPO to exclude kidneys that did not likely need to travel. To understand the spatial relationships of kidney imports and exports, we calculated descriptive statistics for the kidneys that were imported and exported for each OPO and stratified based on the area of the United States defined by the Bureau of the Census: West, Midwest, Northeast, and South (Puerto Rico defined as South for our analysis).

2.3 | High volume by direct air OPO pairs (HVA-OPs)

Next, to determine which OPO pairs were key components of the kidney transportation network, we evaluated all possible OPO pairs in each direction (eg, Baltimore to Los Angeles is different from Los Angeles to Baltimore) and identified the 100 highest-volume OPO pairs. To determine the high-volume pairs that were likely utilizing commercial airlines, we excluded pairs that were connected by land and fewer than 250 miles apart (35 OPO pairs). We matched the high-volume OPO pairs that were located far apart to their local commercial airport options. We excluded OPO pairs that were not connected by at least 1 direct, nonstop flight (7 OPO pairs). The remaining 58 OPO pairs were defined as the High Volume by direct Air OPO Pairs (HVA-OPs) and used for further analysis with flight data.

2.4 | Quantifying flight distribution

With the nodes and connections of the KT network defined, we plotted the number of flights to all airports scheduled daily from January 1 to April 26 in 2019 and 2020 to understand the overall change in commercial flights nationally scheduled pre-COVID-19 to those scheduled post-COVID-19. We used the Mann–Whitney U test to compare the median number of flights per day between the 2 periods. For perspective about the impact of COVID-19 in comparison with another historic event that impacted airlines on September 11, 2001, we plotted the number of US scheduled flights between July 1, 2001 and December 31, 2001.

Next, we conducted the above analysis for the HVA-OPs over the same periods. Furthermore, to understand how these flights were distributed throughout the day, we calculated descriptive statistics for the frequency of scheduled flights in total and by time of day between HVA-OPs for the third week in April 2019 (April 14-20, 2019) and the third week in April 2020 (April 12-18, 2020). Specifically, the time of day was delineated as morning (before noon), afternoon (noon to 5:00 pm), and evening (after 5:00 pm). To determine the number of flights per day, we divided the number of flights in that given week for each time of day by 7. We compared the observed frequencies to the expected historical data using the \( \chi^2 \) test.

2.5 | Next flight out wait time

Since the effect of flight availability on CIT is directly impacted by the wait from when an organ is ready for transportation and the time of the next scheduled flight, we further investigated the relationship between scheduled flights and wait times. We defined Next Flight Out Wait Time (NFOWT) as the time between the most recent flight out departure time and the time of the next scheduled flight (for any HVA-OP this has a distribution from 0 to potentially as high as several days). For example, if the first flight between 2 destinations is at 1:00 pm and the next is at 4:00 pm, the NFOWT would be 3 hours. To calculate the number of flights per day for each HVA-OP, we divided the total number...
of flights in the third week of April 2019 (dates defined above) by 7. To calculate the NFOWT, we divided 24 by the number of flights per day.

2.6 | Changes to NFOWT during COVID-19

To understand the change in wait times based on the change in flights scheduled, we calculated the NFOWT for each HVA-OP in the third week in April 2020. We compared the NFOWT for April 2019 to April 2020 using a Wilcoxon signed-rank test. We defined the change in NFOWT for each HVA-OP as the NFOWT at 1 time subtracted from the NFOWT at a later time (eg, difference in NFOWT for a flight from Baltimore to Los Angeles on April 15, 2020 and April 15, 2019).

2.7 | Cancellations

Historical data on flight cancellations for April and May 2020 were not available, so we prospectively collected data manually by observing the number of cancelled flights for a 1-week period from May 1 to May 8, 2020. The number of flights cancelled each day and the percent change from the day prior was calculated for all commercial airline flights in the United States.

2.8 | Statistical analysis

We performed descriptive statistical analysis on the OPO and airline data. Confidence intervals are reported as per the method of Louis and Zeger. All analyses were performed using Stata 16.1/MP for Linux and using ggplot2 (v.3.3.0) on R (v.4.0.0).

3 | RESULTS

3.1 | Kidney imports and exports throughout the United States

From January 1, 2018 to March 2, 2019, a median of 170 kidneys (interquartile range [IQR] 105-247, Table 1) were exported from an OPO, and a median of 141 kidneys (IQR 80-212) were imported to an OPO. After stratifying by region of the United States, we found the OPOs in the western United States exported the most kidneys with a median number of 208 kidneys (IQR 105.8-268; range 50-383). The northeastern United States imported the most kidneys with a median number of 191 kidneys (IQR 150.8-218.3; range 33-878).

3.2 | The kidney transportation network in the United States

From January 1, 2018 to March 2, 2019, 10 710 kidneys were transplanted that crossed OPO boundaries (were recovered in 1 OPO and transplanted in a different OPO). Of these, 4486 involved the 100 highest volume OPO pairs, that is, the pairs across which kidneys were shared most commonly. Of these 100 OPO pairs, 65 were over 250 miles apart and 58 were 250 miles apart and had a direct flight between them; as described in the Methods section, these 58 pairs are herein referred to as HVA-OPs.

3.3 | High volume by direct air OPO pairs (HVA-OPs)

Kidneys transported between these HVA-OPs represented 2559 kidneys during our study period. The median distance between the OPOs was 445 miles (IQR 342-783). Among OPOs where kidneys originated, 5 had 3 local airport options, 16 had 2 local airport options, and 37 had 1 local airport option. Among OPOs where kidneys arrived, 17 had 3 local airport options, 19 had 2 local airport options, and 22 had 1 local airport option.

3.4 | Flights overall

There was a precipitous drop from 19 811 flights scheduled on March 26, 2020 to 8270 flights on April 14, and then the flights scheduled plateaued (Figure 1). From March 26-April 26, 2020, flights scheduled were 39.0% lower compared to the same period in 2019. For perspective, comparing the impact of COVID-19 to the impact of September 11, 2001, the number of flights in 2001 initially dropped immediately and more severely (due to government grounding of all flights), but returned rapidly to 79.6% of baseline prior by September 17, 2001 (Figure 2).

| Characteristic | Median (IQR) | Range |
|---------------|--------------|-------|
| Exports overall | 170 (105-247) | 35-793 |
| Exports by area of United States | | |
| West | 208 (105.8-268) | 50-383 |
| Midwest | 149 (107.3-224.3) | 47-317 |
| Northeast | 158.5 (70.3-238) | 35-793 |
| South | 170 (107-238) | 5-408 |
| Imports overall | 141 (80-212) | 2-878 |
| Imports by area of United States | | |
| West | 80.5 (33.3-268.5) | 2-828 |
| Midwest | 129.5 (84.3-162.8) | 20-267 |
| Northeast | 191 (150.8-218.3) | 33-878 |
| South | 131 (90-290) | 12-840 |

Note: Areas defined by the Bureau of the Census show highest number of exports are from the western United States while the highest number of imports are to the Northeastern United States. Abbreviation: IQR, interquartile range.
3.5 | Flights within kidney transportation network

National trends of decreased flights were also seen within the kidney transportation network. The median number of flights among the HVA-OPs in the third week of April 2020 was lower than the corresponding number in 2019 (34 vs 112, \( P < .001 \), Figure 3). The impact on HVA-OPs varied widely. Interestingly, 2 HVA-OPs had an increase in flights (OPTN code ALOB to FLMP increased by 7%, and PRLL to FLMP increased by 550%). The remaining 56 HVA-OPs had a median percent decrease of 65.1% (IQR 54.7%-75.3% decrease, range 0%-100% decrease; Figure 4). For example, flights between NCCM and VATB were 28.1% lower (82 postpandemic vs 114 pre-pandemic), while flights between PATF and NJTO were 99.3% lower (1 postpandemic vs 147 prepandemic).

3.6 | Flight distribution by time of day

Nationally, morning flights in the third week of April 2020 were 65.4% lower compared to 2019. Afternoon flights were 65.1% lower, and evening flights were 70.8% lower (all \( P < .001 \)). Among the HVA-OPs, the median number of flights among the HVA-OPs in the third week of April 2020 was lower than the corresponding number in 2019 for morning flights (15.5 vs 42.5; \( P < .001 \); Table 2), afternoon flights (14.0 vs 37.5; \( P < .001 \)), and evening flights (7.0 vs 26.5; \( P < .001 \)). There was considerable variability in the percent decrease in flights for each time of day among HVA-OPs. One HVA-OP had an increase in morning flights (PRLL to FLMP increased by 100%). The remaining 57 HVA-OPs had a median percent decrease of 66.7% morning flights (IQR 50.0%-77.4% decrease; range 0%-100% decrease). For example, the morning flights from the OPO ILIP to the OPO FLMP were 26% lower (77 to 57 flights), while flights from the OPO PATF to the OPO in NYRT were 98.7% lower (77 to 1 flight). Four HVA-OPs had an increase in afternoon flights (PRLL to FLMP increased by 1000%, TNDS to SCOP increased by 100%, LAOP to FLMP increased by 7.7%, and ALOB to FLMP increased by 16.7%). The remaining 54 HVA-OPs had a median percent decrease of 70.2% afternoon flights (IQR 53.2%-83.5% decrease, range 0%-100% decrease). Four HVA-OPs had an increase in evening flights where 3 historically had zero evening flights (PADV to AZOB increased to 11 flights, TNDS to VATB increased to 1 flight, and FLFH to AROR increased to 1 flight), and 1 HVA-OP had an increase in evening flights by 16.7% (MIOP to NYWN). The remaining 54 HVA-OPs had a median percent decrease of 72.0% evening flights (IQR 53.0%-85.3% decrease; range 0%-100% decrease).

3.7 | Changes to NFOWT during COVID-19

The NFOWT for HVA-OPs significantly increased from median 1.5 hours (IQR 0.76-3.3) in the third week of April 2019 to 4.9 hours (IQR 2.6-11.2; \( P < .001 \)) in 2020 (1 HVA-OP did not have a NFOWT for April 2020 because their flight volume was reduced to zero). The change in NFOWT was a median increase of 2.7 hours (IQR 1.3-4.5), meaning that an OPO pair had to wait a median 2.7 hours longer for a flight between the 2 OPOs in the third week of April 2020 compared to 2019. There were 4 HVA-OPs that had stability or increase in the number of flights scheduled in April 2019 compared to April 2020, so the change in NFOWT was less than or equal to zero. The smallest increase in change in NFOWT was 0.46 hours (CAOP to CADN): flights between this pair decreased from 137 to 38 flights per day, corresponding to an increase in

![FIGURE 1](image-url) Number of flights per day scheduled in the United States across all airports and across the Organ Procurement Organizations with the highest volume. The black vertical line on March 13 represents the day the federal government declared a national emergency. There is a precipitous drop starting March 26, 2020 [Color figure can be viewed at wileyonlinelibrary.com]
The greatest increase in NFOWT was 139 hours (PATF to NYRT and PATF to NJTO): flights per week between these pairs decreased from 147 to less than 1 flight, corresponding to an increase in NFOWT from 1.1 hours to 7 days.

### 3.8 | Cancellations

In the first week of May 2020, cancellations dropped from 2630 on May 1 to 246 on May 8. This correlated with a substantial drop in the number of scheduled flights. This is presumably because airlines...
were reducing their schedules rather than scheduling optimistically and cancelling at the last minute.

4 | DISCUSSION

In this national study of the kidney air transportation network in the United States pre- and post-COVID-19, we found the number of domestic flights scheduled overall were 39.0% lower between March 26 and April 26, 2020 compared to the same period in 2019. We found the number of flights between HVA-OPs—OPO pairs between which kidneys historically most likely traveled by direct flight—were 65.1% lower in April 2020 compared to April 2019 ($P < .001$). This lower flight availability affected some HVA-OPs more than others, with some losing 100% of flight options. Further, the HVA-OPs had an increase in wait time between flights from a median of 1.5 hours in 2019 (IQR 0.76-3.3) to 4.9 hours in 2020 (IQR 2.6-11.2, $P < .001$), with some wait times between flights increasing by a magnitude of days. While commercial airlines compared to chartered transport of organs are cost-effective$^{19,20}$ and generally safe,$^{2,20-22}$ discussions about the flight network of kidney transportation and the potential shortcomings are often neglected. We highlight here the significant effect of the pandemic on airlines that will potentially limit the availability of organs, increase CIT, and increase the risk to organs during delivery.

With the challenges of flight availability, a natural, immediate mitigation might be to reduce broader sharing. While this might address the logistical concerns associated with organ transport, this would no doubt harm the goals of wider organ distribution. Instead, a better mitigation might be to improve mechanisms for KT transport. If kidneys could be shipped on preservation pumps, this might reduce the impact of transportation delays on delayed graft function. Another consideration could be less reliance on commercial travel and more reliance on charter travel when necessary; this certainly occurs with other organs, although the potential costs of such an approach would need to be carefully considered. Our findings motivate an exploration of creative approaches to KT transport as the impact of this pandemic on the airline industry evolves.

Our findings of many cancellations (2630 flights per day) at the beginning of May and the subsequent drop in cancellations represent the rapid changes in the airline responses to the pandemic. For example, Delta reduced the scheduled flights by 80%$^{23}$...
for the second quarter of 2020 yet averaged 0% cancellations in early May. Southwest averaged more than 1450 (50%) cancellations in that same period. The nation’s largest airline, American Airlines, was averaging more than 320 (17%) cancellations daily. Cancellations as opposed to fewer flights scheduled are critical because these would represent instances where a kidney expected a scheduled flight but resulted in hours waiting at the donor airport. This increased and unpredictable waiting could significantly increase CIT while worsening recipient posttransplant outcomes. Further study of cancellations will be required to see whether airlines respond to last-minute cancellations or more permanent changes in schedules.

Our findings do not only apply to solid organ transplantation. Stem cell transplantation has congruent problems. In relation to transplantation supply concerns, Szer et al describe travel restrictions and the risk of COVID-19 infection impeding the provision of donor hematopoietic stem cells. These cells are stored fresh or frozen and require timely transport across national borders. Therefore, focusing only on the issues and solutions for transporting kidneys around the country restricts our ability to leverage other transplant-related factors that rely on an optimal transportation network. We should approach the transportation problem from the perspectives of multiple organs for the OPTN to reach fruition.

The recent changes to the organ allocation system have shed light on the need for enhanced transportation management. The current transportation solutions used by the OPTN have evolved over time, and its management is decentralized. There is limited tracking and monitoring of transportation data (eg, travel time). Further, there are currently no standard transportation guides to identify and address safety, service, and cost concerns. These challenges are not insurmountable but will require a centralized and holistic approach leveraging multifaceted solutions integrated into the transportation network. The transportation network must maximize current capacity, identify new transportation options, and have real-time visibility into transportation movements to optimize air and ground operations.

Our study must be understood in the context of its limitations. Synthesizing different data sources based on different elements and granularity can intersect some variability. Additionally, we used a cutoff of 250 miles to represent commercial air travel; helicopter use could be an alternate transportation method, but prior studies describe only 3% of OPOs using helicopters frequently and, even then, more than 250 miles would be a considerable distance that would probably merit commercial air travel. Lastly, granular data about connections and delays were not available, so we only studied direct flights. However, many kidneys might travel on connecting flights. While we cannot make direct inference about connecting flights, there are reports of increased connection times due to new safety regulations that decrease flight connectivity. In addition to the potential delays of the kidneys themselves, a breakdown of the commercial transport network will likely also impact the ability to share donor blood in advance of transplants, particularly for highly sensitized patients. Those cases might require mitigation through predecency patients and sharing of donor blood so crossmatching can be performed prior to the accrual of cold ischemia time. That said, data are currently unavailable for how often this scenario arises and how often it relies on commercial transport; a more organized national transportation system could start to help better understand this practice. As such, if anything, our findings are probably an underestimate of the true impact of the pandemic on the kidney transportation network.

In summary, transportation of kidneys via commercial airlines represents a significant and indirect impact of COVID-19 on the kidney transplantation community. Patients, providers, transplant centers, and OPOs turn to United Network for Organ Sharing, the federal government, and the airline industry for policies that will address this concern. COVID-19 has disrupted the world and is requiring us all to live life differently. Our findings highlight the importance of this supply chain in our field and emphasize the need to create logistic solutions specifically for the organ donation and transplant community.

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DISCLOSURE
The authors of this manuscript have conflicts of interest to disclose as described by the American Journal of Transplantation. Mr Cartier, Mr Roush, and Mr Gunning are employees of cHealthWorks Logistics. Mr Cartier, Mr Roush, and Mr Gunning own shares in cHealthWorks Logistics. The rest of the authors have no conflicts of interest to disclose.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the SRTR. Restrictions apply to the availability of these data, which were used under license for this study. Data are available at https://www.srtr.org/ with the permission of the SRTR.
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