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ABSTRACT

We study disparities in liver transplant allocation when innovation alleviates the scarcity of organs. When direct-acting antivirals for Hepatitis C (HCV) reduced HCV+ liver demand, we show a disproportionate increase in White HCV- liver transplants (56.6%) relative to Black HCV- transplants (11.9%). The time to transplant decreased (31.1%), and the transplant rate increased (19.5pp), only for White HCV-patients. Our results are surprising because liver health is the primary determinant of transplant priority and marginal White patients were of better liver health. We show more similar gains when we focus on privately insured patients and/or areas with more Black patients.

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1 Introduction

Medical innovation has the potential to alleviate resource scarcity, but its benefits are not always distributed equally across populations. Organ transplantation offers a useful setting in which to examine this concern, as gains from treatment advances depend on a patient's ability to navigate the complex transplant process. We study this dynamic by examining the 2014 introduction of direct-acting antiviral therapeutics (DAAs) for the treatment of chronic hepatitis C infection (HCV). By raising HCV viral clearance rates to over 90%, DAAs dramatically reduced the demand for liver transplants among HCV^+ end-stage liver disease (ESLD) patients. The result was a significant increase in the number of donor livers available to patients with other forms of ESLD (henceforth HCV^-), including alcoholic liver disease and liver cancer. Historically, Black HCV^- patients were 40% less likely than White patients to join the liver transplant waiting list, but conditional on listing, they were 40% *more* likely to receive a transplant.[1] This higher transplant rate among Black patients reflects selection: relative to White patients, Black patients tend to have more advanced liver disease at the time of listing, and liver health is the primary determinant of donor liver allocation.[2] This pattern highlights how clinical need interacts with resource allocation mechanisms, raising broader questions about who stands to gain when new technologies improve access to limited resources. Thus, the stylized research question we ask is: When medical innovation relieves pressure on scarce resources—as DAA therapy did by reducing demand for liver transplants among HCV^+ patients—are the resulting gains equitably distributed between Black and White patients?

Using data on the universe of liver transplant waiting list registrations and transplants from 2005 to 2019, we find that White HCV^- patients disproportionately benefited from the increase in donor liver availability that followed the introduction of DAAs for HCV. We show that the increased relative availability of donor livers created an incentive for marginal HCV^- patients to register for the waiting list, and we document larger flows of HCV^- White patients onto the list (46.3% increase from baseline) than HCV^- Black patients (22.4% increase from baseline). Importantly, White HCV^- patients who joined the waiting list after DAAs did not change the health composition of the waiting list – Black waiting list registrants remained in significantly worse liver health. Surprisingly then, we find a 56.6% average annual increase in the count of liver transplants for White HCV^- patients, but only an 11.9% increase for Black HCV^- patients. Furthermore, for White HCV^- patients, we estimate an average annual increase of 19.5 percentage points in the transplant rate (i.e., transplants conditional on listing) and a 31.1% reduction in the time from listing to transplant; we find no economically or statistically meaningful changes in these measures for Black patients. To put these results in context, prior to DAAs, 75% of HCV^- liver transplants went to White

[1] A large medical and public health literature has documented similar disparities (Rosenblatt et al., 2021; Wahid et al., 2021; Jesse et al., 2019; Bryce et al., 2010, 2009).

[2] Liver health is measured by the Model for End-Stage Liver Disease (MELD) score. Among patients listed for liver transplant from 2005 to 2013, Black patients had MELD scores that were 17% higher (worse) than White patients at the time of listing.

patients, but our results imply that 85% of transplants that can be causally attributed to DAA-driven reallocation went to White HCV^- patients.

Our results are evident in trends from raw data, however we focus on a research design that studies behavior (i.e., listing decisions) and outcomes (i.e., transplants) among HCV^- ESLD patients relative to similar trends for end-stage renal disease (ESRD) patients before and after the introduction of DAAs. Since DAAs are not an effective treatment for ESRD, this group serves as a plausibly unaffected counterfactual, allowing us to net out concurrent shocks such as the Affordable Care Act's Medicaid expansions or the opioid crisis, which have both been shown to influence the demand and supply of transplantable organs (Lemont, 2023; Dickert-Conlin et al., 2024). We show robustness of our main findings through a triple differences design in which we compare outcomes before and after DAA availability, across organs, and across markets with above and below median baseline HCV^+ transplant rates. The argument for the third difference is that markets with high HCV^+ transplant rates prior to the introduction of DAAs should, all else equal, see larger reductions in the demand for liver transplant from HCV^+ patients. Additionally, this strategy nets out race-group specific differences in the proportional contribution in each organ market. Results from these triple-difference models are consistent with our main difference-in-differences findings that DAAs disproportionately benefited White patients.

To understand these results, we investigate a variety of mechanisms. First, we consider racial concordance, the idea that waiting list registrants are more likely to be offered an organ from a donor of the same race. We show that DAAs had no effect on the racial composition of deceased donor organs, eliminating the possibility that higher same-race match rates would drive disproportionate gains for either group.[3] Next, we consider whether the disproportionate increase in White waiting list additions shifted the racial composition of the list towards White patients. In fact, we show no effect of DAAs on the racial composition of the list, consistent with the findings that both additions (i.e., flows) and transplants (i.e., exits) increased disproportionately for White patients. We also show no effects on waiting list mortality, which rules out the idea that the composition of the list changed on other dimensions of health. Instead, we uncover evidence that patient resources matter in who benefits from innovation. When we focus on those under age 65 with private insurance, the gaps in the gains from DAAs are considerably smaller. Similarly, we find narrower differences in gains when we focus on donor service areas with more Black patients and *wider* differences when we focus on donor service areas with more White patients. In sum, in a setting in which allocation should be relatively algorithmic based on medical need, we find that White patients enjoyed an outsized share of the gains from innovation, and we uncover evidence consistent with both patient resources and local racial compositions playing important roles.

We contribute to the economic literature that has found medical innovation to both be overwhelmingly welfare

[3]Black HCV^+ transplants fell by similar percentage relative to White HCV^+ transplants (-33.0% vs. -32.2%).

improving in the long-run (Ho & Pakes, 2024; Dranove et al., 2022; Hall & Jones, 2007; Murphy & Topel, 2006; Cutler & McClellan, 2001; Newhouse, 1992) and produced and diffused unequally across groups in the short-run (Cutler et al., 2012; Koning et al., 2021; Alsan et al., 2023; Glied & Lleras-Muney, 2008; Hoagland, 2024). Disadvantaged groups may lack access to innovations or face constraints that prevent adoption, such as travel costs or labor market frictions (Papageorge, 2016; Hamilton et al., 2021). A large literature recognizes that, even when product and procedure innovations pass benefit-cost tests overall, these new technologies can increase inequality, especially in the short-run (Aghion et al., 2018; Jaravel, 2018). In our case, conditional on listing and prior to DAAs, Black HCV^- patients were more likely to receive a transplant because of worse liver health, but the effect of innovation was to disproportionately benefit White patients, equalizing rates of transplantation even though marginal Black patients had greater medical need.

We also contribute to a large economic literature on Black/White gaps in healthcare access and health outcomes (Hollingsworth et al., 2024; Zewde, 2024; Arias et al., 2022; Kuziemko et al., 2018; Wherry et al., 2018). This literature emphasizes Black/White disparities in both insurance rates and insurance type as driving differences in outcomes, while also demonstrating that gaps persist even after accounting for insurance status. In our case, among privately insured patients, we find that DAAs increased transplant rates for both Black and White HCV^- patients, and while the improvement remains larger for White patients, the difference between groups is not statistically significant. However, within this subgroup, DAAs still led to statistically larger increases in both waiting list registrations and total transplant counts for White HCV^- patients.

Finally, our work speaks to the growing literature on algorithmic decision-making that may, or may not, exacerbate health disparities (Obermeyer et al., 2019; Rambachan et al., 2020; Arnold et al., 2021; Hurtado & Sakong, 2024). The Model for End-Stage Liver Disease (MELD) score quantifies a patient's liver function by predicting their short-term mortality risk. Conditional on biological compatibility, the MELD score is the primary metric used to allocate donor livers based on medical need. We show that before and after DAAs, the mean MELD score of Black registrants at listing remained roughly 15% above that of White registrants, reflecting greater illness severity among Black patients. Prior to DAAs, this translated into a higher transplant rate for Black HCV^- ESLD patients relative to White patients. However, despite Black patients continuing to present with more advanced liver disease at listing, the Black-White gap in transplant rates *narrowed* following the introduction of DAAs, as White patients saw disproportionate gains.[4] Our results suggest that complementary policies may be needed to ensure equitable distribution of organs (Fleurence & Collins, 2023; Auty et al., 2022), including adjustments to the MELD score. This has implications for organ allocation policy, as future medical innovations that reduce demand for organs in

[4]Recent reporting suggests that organ allocation is increasingly separate from medical necessity. https://www.nytimes.com/interactive/2025/02/26/us/organ-transplants-waiting-list-skipped-patients.html

other therapeutic areas could create similar distributional challenges. More broadly, our work implies that standard approaches to valuing medical innovations, which typically focus on direct therapeutic benefits and overall cost-effectiveness, may need to account for both the magnitude and the distribution of externalities (particularly in the absence of prices) to capture their welfare implications.

2 Background

When a patient's liver disease has progressed to liver failure (i.e., end-stage liver disease) the only viable treatment option is transplant. The liver transplant process includes three distinct phases, each with opportunities for disparities. At the evaluation phase, patients are referred to a transplant center to complete a series of medical and psychosocial workups that may include assessing the degree of social support available to the candidate, psychiatric illness, and whether the candidate uses alcohol, tobacco, or other substances (Wahid et al., 2021). Disparities in referrals to the evaluation phase are not well documented on a large scale, though a few small scale (i.e., single transplant center) studies point to lower referral rates for women, racial and ethnic minorities, those without private insurance, and those with alcohol-associated liver disease (ALD) (Bryce et al., 2009; Julapalli et al., 2005).

Greater attention has been given to the role of disparities when progressing from the evaluation phase to the liver transplant waiting list. Overall, rates of listing among those who have been evaluated for transplant range between 30% and 50%, however several studies have documented variation in listing rates across various subgroups (Rosenblatt et al., 2021; Jesse et al., 2019; Bryce et al., 2010, 2009). A notable challenge in determining rates of listing disparities is that the liver disease burden is not distributed proportionally across subgroups, meaning that comparisons of listing rates to population distributions will lead to inaccurate measures of listing disparities. To address this challenge, researchers have scaled listing counts by group-specific deaths from ESLD in an attempt to approximate subgroup disease burdens. For example, using a listing-to-death ratio, Rosenblatt et al. (2021) found that Black ESLD patients were 27% less likely to join the liver transplant waiting list than White ESLD patients between 2014 and 2018.

Finally, disparities may be present among those who have registered for the liver transplant waiting list, but have yet to receive a transplant. Prior to 2002, transplant priority among those listing was determined by time accrued on the waiting list, hospitalization status, and an index comprised of five clinical measures (Cholongitas et al., 2005). This allocation mechanism disadvantaged people who tended to list later in their disease progression (i.e., racial and ethnic minorities) and, as a result, prior research concluded that Black patients were less likely to receive a transplant conditional on listing and more likely to become too sick to transplant or die while on the waiting list (Reid et al., 2004). Due in part to these perceived inequities and concerns over the ability to manipulate waiting list priority, the

Organ Procurement and Transplantation Network (OPTN) issued a final rule in October 1999 calling for revisions to the liver allocation criteria (OPTN, 1999). Those revisions resulted in the adoption of the Model for End-Stage Liver Disease (MELD) score in 2002 as the mechanism to determine deceased donor liver allocation among waiting list registrants (Trivedi, 2022). The MELD score is intended to quantify the 3-month mortality risk for individuals with ESLD, where a higher score corresponds to a higher mortality risk. In its current iteration, the MELD score is comprised of clinical measures (i.e., serum bilirubin, serum creatinine, serum sodium, and prothrombin time) along with an indicator for whether the individual received 2 or more dialysis treatments within the past week, and does not consider time spent on the waiting list or hospitalization status (Kim et al., 2021).

There is conflicting evidence on the degree to which disparities in transplant outcomes conditional on listing persist in the post-MELD era. Moylan et al. (2008) concluded that while Black race was associated with a lower probability of liver transplant within three years of listing and a higher probability of becoming too sick to transplant or dying before the introduction of the MELD score, these associations were no longer present after the MELD score had been introduced. However, several other studies have contradicted this finding and continue to report evidence of transplant disparities by race in the post-MELD period (Nephew & Serper, 2021).

We focus on the second (listing) and third (transplant) phases of this process. The dramatic decline in HCV^+ liver demand caused by DAAs created an incentive for marginal, clinically eligible HCV^- patients to join the waiting list, and our analysis first uncovers differences in listing by race. Understanding these differences is critical for assessing the effects of DAAs on HCV^- transplant outcomes as changes in marginal patients joining the waiting list may alter its racial, socioeconomic, and clinical composition. We then examine how DAAs affected racial disparities in transplant rates and time to transplant, holding the waiting list size constant.

3 Data

We use data from the Scientific Registry of Transplant Recipients (SRTR) from 2005 through 2019.[5] The SRTR data include comprehensive individual-level information on organ transplant waiting list registrants, donors, and recipients, collected from the Organ Procurement and Transplantation Network (OPTN) through the United Network for Organ Sharing (UNOS) (Wright, 2022).[6] The data include measures of health that enter the MELD score both at the time of registration and at the time of transplant. Registrants are recorded as leaving the waiting list in the event of transplant or attrition through death or becoming too sick for transplant. Rarely, a patient's

[5] The SRTR data system includes data on all donor, wait-listed candidates, and transplant recipients in the United States, submitted by the members of the Organ Procurement and Transplantation Network (OPTN). The Health Resources and Services Administration (HRSA), U.S. Department of Health and Human Services provides oversight to the activities of the OPTN and SRTR contractors.

[6] Though rare, some people receive a liver transplant without registering for the waiting list. We include these cases in our transplant measure.

health will improve causing them to leave the list.

The SRTR data collect HCV antibody test results for transplant recipients, but do not directly measure HCV status at the time of wait-listing. Therefore, to determine whether a registrant was HCV^+ at listing, we examined the frequency at which different primary diagnosis codes commonly occurred among liver transplant recipients with and without HCV. For example, 59% of HCV^+ transplant recipients have a diagnosis of "cirrhosis: type C" (SRTR code 4204) compared to only 2.2% of HCV^- recipients. Similarly, "alcoholic cirrhosis with hepatitis C" (SRTR code 4216) is observed in 13.3% of HCV^+ transplant recipients and only 0.6% of HCV^- recipients. Conversely, "cirrhosis: fatty liver (NASH)" (SRTR code 4214) is found among 14.3% of HCV^- transplant recipients compared to only 0.6% of HCV^+ recipients. Likewise, "alcoholic cirrhosis" (SRTR code 4215) is present in 26.7% of HCV^- transplant recipients and only 3.5% of HCV^+ recipients. We then classify a code as indicative of HCV status only if its frequency in one group (either HCV^+ or HCV^- transplant recipients) exceeded that of the other group by a factor of at least four (Callison et al., 2024). Additionally, the SRTR data include an optional text field containing supplementary diagnostic information that we use to further refine our HCV classifications. Examples of text in this field include terms such as "HCV," "Hepatitis C," "Hep C," and variations that may include periods, dashes, slashes, or minor typos.[7]

While we have data on the confirmed HCV status of transplant recipients, for consistency across outcomes, we use inferred status in all analyses. To the extent that inferred HCV status leads to misclassification, as some HCV^+ individuals are categorized as HCV^- (and vice versa), any bias introduced will likely attenuate our estimated effects. Since HCV antibodies are detectable even after viral clearance, we use antibody status at the time of transplant to evaluate whether individuals we classify as HCV^- might include those who had cleared the infection, which could overstate the impacts of DAAs on HCV^- wait-listing. Our findings indicate this is unlikely. For instance, in 2014, 99 (3.2%) of the 3,128 liver transplant recipients categorized as HCV^- based on diagnostic codes tested positive for HCV antibodies at transplant, compared to 206 (3.3%) of the 6,180 categorized as HCV^- in 2019. Finally, the available diagnostic codes and text descriptions do not allow us to determine HCV status in approximately 15% of registrants, so we exclude these individuals from our analyses.

Table 1 presents counts, means, and proportions of the endogenous variables by time period (before and after DAAs), HCV status, and, as a source of comparison that we utilize below, for kidneys. We present these statistics in two panels representing White and Black patients.[8] The Table presents statistics on the average annual count of waiting list additions, the average annual count of ESLD/ESRD deaths, and their ratio, which serves as a proxy

[7] Including information from this text field yielded an additional 1,804 HCV^+ registrants (roughly 120 per year) to the 93,547 registrants (roughly 6,236 per year) who we identified as HCV^+ or HCV^- through diagnosis codes alone.

[8] While we focus on these two groups, our sample also includes individuals identifying as Hispanic, Asian, Pacific Islander and Native American. Because our focus is on gaps between Black and White patients, we control for differences in these groups, but we do not report their effects.

listing rate as discussed above. Table 1 also shows the mean initial MELD score (i.e., liver health) at the time of wait listing and at transplant. There is not a comparable summary health measure for kidneys. The Table shows time to transplant in days, the mean annual count of transplants, and the transplant rate, defined as the total number of transplants divided by average number of registrations on the waiting list throughout the year.

Statistics on HCV^+ waiting list registrations and transplant counts convey the magnitude of the direct impact of DAAs on liver allocation. For example, for White HCV^+ patients, average annual waiting list additions fell from 2,701 to 1,580 between the period prior to DAAs (2005-2013) and after DAAs (2014-2019). Similarly, White HCV^+ average annual transplants fell from 1,473 to 1,049. Table 1 shows similar declines for Black patients. The HCV^+ liver columns demonstrate how DAAs obviated the need for a transplant for many HCV^+ patients and created an increase the availability of deceased donor organs for HCV^- patients.

For HCV^- White patients, average annual additions to the waiting list (i.e., the flow onto the list) increased from 3,832 to 5,682, and the average count of annual ESLD deaths fell from 65,837 to 60,245 following DAAs.[9] The ratio of additions to deaths, which proxies for the accessability of the waiting list, increased from 0.064 to 0.077. For White patients, both the MELD score at wait listing (WL) and at transplant (TX) increased (18.8 to 19.7 and 23.0 to 24.1, respectively), suggesting that marginal White patients were of worse liver health following DAAs. However, conditional on receiving a transplant, the time to transplant fell from 239 days to 216 days. Ultimately, the average count of annual liver transplants for White HCV^- patients increased from 2,058 to 3,385, and the transplant rate increased from 0.322 to 0.503.

For Black patients, the average annual count of HCV^- waiting list registrations also increased after DAAs became available (from 365 to 499). However, unlike White HCV^- patients, Black patients also experienced an increase in average annual ESLD deaths, from 9,368 to 10,914. Although the ratio of waiting list additions to deaths improved slightly for Black HCV^- patients (0.039 to 0.046), the gap between the Black and White ratios actually widened over this period. As with White HCV^- patients, newly listed Black HCV^- registrants presented in worse liver health as measured by the MELD score (22.7 to 23.1), as did newly transplanted Black patients (26.4 to 27.0). Black HCV^- patients saw other improvements with the introduction of DAAs: average time to transplant fell from 201 to 192 days, average annual transplants increased from 220 to 317, and the observed transplant rate increased from 0.452 to 0.601. However, these improvements were modest in size compared to the gains experienced by White HCV^- patients.

The presentation of summary statistics for HCV^- liver patients and kidney patients hints at our research design. Changes in trends in HCV^- liver behaviors and outcomes following the introduction of DAAs may be due to DAAs or

[9] Greater HCV^- waiting list enrollment could be due to behavioral factors (e.g., improved transplant odds resulting from lower HCV^+ demand) or increasing disease prevalence. However, Callison et al. (2024) shows that the majority of the post-DAA increase in HCV^- listing is associated with alcoholic liver disease (ALD) and that the prevalence of ALD is flat during this period.

other, concurrent shocks. The kidney comparison allows us to formulate a counterfactual trend in these behaviors and outcomes that should not be affected by DAAs. For example, kidney waiting list registrations increased marginally following DAAs from 15,830 to 16,049, which is smaller than the White HCV^- liver waiting list addition change, but which would suggest an attenuated effect of DAAs on the flow onto the waiting list. For White patients, similar changes occurred for the annual count of transplants. Kidney transplant counts increased from 8,323 to 8,743, which again would attenuate the effect of DAAs on HCV^- transplants. For Black HCV^- patients, waiting list additions, transplants, and the transplant rate all increase, but in each case, relative to the changes in kidneys, the increases are attenuated. Appendix Figures 1 and 2 present the log counts of waiting list additions and transplants by race and organ over time. These figures show a clear inflection point in 2014, with sharp declines in HCV^+ liver waiting list additions and transplants across both racial groups coinciding with the introduction of DAAs. For White HCV^- patients, there is a marked and sustained increase in liver waiting list additions and transplants, while the increases for Black HCV^- patients are more muted. Kidney trends are more stable by comparison, though we do observe some post-2014 increases in kidney waitlisting, particularly for Black patients around 2017, and transplant counts for both Black and White patients. These changes likely reflect concurrent shocks such as the opioid crisis or Medicaid expansion, reinforcing the importance of including a comparison group to net out the influence of these potential confounders.

Appendix Figure 3 plots liver transplant rates for HCV^- waiting list registrants by race over the sample period. After declining for several years prior to the introduction of DAAs, transplant rates increased for both Black and White HCV^- patients after 2014. However, where the Black transplant rate was substantially higher than the White rate in the pre-DAA period, by 2019 the rates had converged.

National-level statistics presented in Table 1 should not be interpreted as causal evidence of the effects of DAAs on behavior and outcomes because, within organ, the statistics average over several years (i.e., pre-DAAs, 2005 to 2013, and post-DAAs, 2014-2019), and there exists spatial variation in the allocation of organs across donor-service areas. In the next section, we estimate formal difference-in-differences estimators, along with time-disaggregated event studies, for HCV^- liver patients relative to kidney patients before and after DAAs became available. Importantly, we control for both DSA-by-organ and year fixed effects, which absorb unobserved heterogeneity over time and space.

4 Research Design and Results

We estimate the following difference-in-differences (DD) specification separately for each racial group:

$$Y_{dlt} = \beta[\mathbb{1}(l = liver) \times DAA_t] + \gamma_{dl} + \eta_t + \epsilon_{dlt}, \tag{1}$$

where Y_{dlt} represents a dependent variable for donor-service area d, organ l, and year t. For most dependent variables, Y represents a count variable, and we estimate these equations via Poisson regressions. Our coefficient of interest is β, which measures deviations for livers (relative to kidneys) following DAAs. We also include DSA-by-organ, γ, and time, η, fixed effects.

Table 2 reports race-specific estimates of β, DSA-clustered standard errors, and the baseline means of each dependent variable. The first column of Table 2 presents our estimates of changes in liver transplants for HCV^+ ESLD patients associated with the introduction of DAAs. Relative to baseline means, estimates in Column 1 suggest that HCV^+ transplants fell by 32.2% and 33.0% for White and Black patients, respectively. As in Table 1, results on HCV^+ behavior and outcomes convey the magnitude of the direct impact of DAAs on HCV^+ patients.

Turning to HCV^- patients, Column 2 of Table 2 includes estimates for HCV^- average annual waiting list additions by racial group. White HCV^- patients experienced the largest waiting list response, with an increase of 46.3% from baseline, while Black HCV^- patients had smaller listing gains of 22.4% from baseline. Column 3 of Table 2 presents estimates of the effect of DAAs on the average annual count of liver transplants to HCV^- recipients by race. Relative to their respective baseline means, DAAs increased average annual liver transplants by 56.6% for White HCV^- recipients and 11.7% for Black HCV^- recipients. Column 4 of Table 2 includes estimates of the effect of DAAs on the average number of days from joining the waiting list to receiving a transplant for HCV^- recipients by race.[10] The results indicate that the introduction of DAAs led to a reduction in the waiting time for liver transplants for White (31.1%) recipients. In contrast, we find no evidence of reduced times from listing to transplant for Black liver transplant recipients. Finally, Column 5 of Table 2 provides estimates of the effect of DAAs on the liver transplant rate by race. Unlike in Table 1, in which we present national transplant rates per year, in our regressions, we define the transplant rate as the number of transplants in a given DSA/year divided by the number of DSA waiting list registrants, and we calculate separate rates for each racial group. The purpose of examining transplant rates in addition to transplant counts is that conditioning on the size of the waiting list effectively removes the influence of DAA-induced changes to waiting list inflows and outflows, allowing us to assess how DAAs affected HCV^- transplants independent of changes in the waiting list. Notably we find that DAAs only improved HCV^- transplant rates for White recipients (19.53 percentage points).[11] Results in Table 2 show that the gains associated with DAAs went disproportionately to White HCV^- ESLD patients. Indeed, while 75% of transplants went to White patients prior to 2013, estimates in Table 2 imply that 85% of transplants that may be causally attributed to DAAs went to White patients.

[10] The sample for the time-to-transplant analysis is restricted to those who actually received a liver or kidney transplant.

[11] Appendix Table 1 shows how estimates of β change with the inclusion of year and dsa-by-organ fixed effects. The inclusion of year fixed effects significantly attenuates the estimate for the Black transplant rate, which suggests that averaging over post-DAA years (as in Table 1) masks important trends in the transplant rate. The year fixed effects are important in explaining the difference between the unadjusted rates in Table 1 and our difference-in-differences estimates in Table 2.

To demonstrate parallel pre-trends in these outcomes relative to our kidney comparison, we also estimate a time-disaggregated (i.e., event study) version of our DD specification separately by race,

$$Y_{dlt} = \sum_{k=2005}^{2019} \beta_k[\mathbb{1}(l = liver) \times \mathbb{1}(t = k)] + \gamma_{dl} + \eta_t + \epsilon_{dlt}, \tag{2}$$

where the effect of DAAs is allowed to vary over time relative to the baseline normalization in year 2012.[12] All other elements of the model presented in Equation 2 are defined as in Equation 1. Figure 1 presents event study estimates for log transplant counts and transplant rates for White and Black patients. For both outcomes measures, we find little evidence of systematic differential pre-trends for either racial groups, supporting the validity of the research design. Consistent with our results in Table 2, we find large gains in transplant counts in Figure 1a for White patients but considerably noisier effects on log transplant counts for Black patients (Figure 1b). Similarly, we find a considerable increase in the transplant rate for White patients (Figure 1c) but no measurable effect for Black patients (Figure 1d). Appendix Figures 4 and 5 present event studies for White and Black patients for waiting list additions and the time from listing to transplant, each of which show similar effects to those in Table 2 and parallel pre-trends. For both Black and White patients, Appendix Figure 6 shows null effects in events studies of waiting list mortality.

Our primary concern with the research design of comparing trends in liver transplant behavior and outcomes to kidney transplant behavior and outcomes is that the effects of DAAs may spillover to kidney patients. For example, the willingness of ESRD patients to accept an HCV^+ kidney may increase with DAA availability, causing an increase in kidney transplants. As another example, the supply of kidneys may increase if newly cured HCV^+ patients are thus eligible for kidney donation. Callison et al. (2024) document robust evidence that such spillovers are unlikely to affect the qualitative conclusion that DAAs caused a significant externality to HCV^- patients, but in our setting, concern remains that these spillovers would have differential effects by race. To address this concern, we consider a triple differences strategy that exploits variation in the HCV^+ transplant rate prior to DAAs as an economically important determinant of where we should observe greater HCV^- transplants following DAA availability. This triple-differences design also nets out race-group specific differences in the proportional contribution in each organ market. These results are presented in Appendix Table 2 for waiting list additions, transplants, time to transplant, and the transplant rate by race. In all cases, the triple-differences terms (i.e., the interaction between the post period, race, and being in an above median HCV^+ DSA) point in the direction of our results in Table 2, although we lose precision in these estimates.

We present two additional robustness exercises. First, we show robustness to our transplant rate definition. In

[12] We chose 2012 as the baseline year because DAAs were approved by FDA in December, 2013.

Appendix Table 3, alongside estimates of our preferred transplant rate, we also present results on the total number of transplants divided by number of unique registrations that were on the list and waiting at any point during the year. Here, the effects are attenuated for both Black and White patients, but the White effect remains roughly four times larger. Second, because our interest is in differences in behavior and outcomes across races, changes in the racial composition of the liver transplant waiting list as a result of the introduction of DAAs is a concern. Indeed, the percentage flow effects in Table 2 differ markedly by race. However, Appendix Table 4, which shows difference-in-differences estimates of the share of each racial group comprising the liver transplant waiting list, indicate no statistical changes in waiting list racial composition as a result of DAAs.

5 Mechanisms

One straightforward explanation for the disproportionate gains for White HCV^- patients would be that marginal White patients (i.e., those induced to join the waiting list because of the increased donor liver availability due to DAAs) were in worse liver health. In fact, Figure 2a shows the opposite: MELD scores at listing are flat through the introduction of DAAs and consistently higher (i.e., worse) for Black patients (≈ 23) than for White (≈ 20) patients. We observe a similar pattern in MELD scores at the time of transplant. In Figure 2b, the Black/White gap in MELD at transplant remains approximately 3 MELD points before and after DAAs became available. While we cannot estimate an event study for either MELD measure because a similar summary measure does not exist for kidneys, evidence in Figure 2 suggests that Black patients remain in worse health both at listing and at transplant following the introduction of DAAs. Our conclusion is that White patients did not experience disproportionate gains due to medical need relative to Black patients.

Next, we investigate heterogeneity in our main effects by geography. The first two columns in Table 3 report estimates of the effects of DAAs on transplants and the transplant rate for HCV^- White and Black ESLD patients in DSAs with an above median fraction of registrants (non-HCV, both LI and KI) that exited the waitlist from 2005-13 who are non-hispanic Black. This analysis is motivated by research showing that racial representation in health care settings can influence disparities in access and outcomes (Alsan et al., 2019). In our context, DSAs with more Black registrants may reflect settings where Black patients face fewer structural barriers to waitlisting and transplant or are better able to navigate the transplant process. The first two columns of Table 3 show statistically similar increases in the transplant rate between White and Black patients in areas with more Black patients (in contrast to Table 2, in which we found dramatically larger effects on the transplant rate for White patients). We repeat this exercise for donor service areas with above median fractions of registrants (non-HCV, both LI and KI) that exited the waitlist from 2005-13 who are White. In columns 3 and 4 of Table 3, we find large and significant increases in transplant

counts and the transplant rate for White patients, but we find *negative* effects on both outcomes for Black patients. In the context of liver transplants, these results suggest that the racial incidence in the gains from innovation depend significantly on the racial composition of the local area. Appendix Tables 5 and 6 present results on all behaviors and outcomes for above median Black and above Median White DSAs, respectively.

We also explore the role of payer in the allocation of livers for transplant. In the final two columns of Table 3, we focus our analysis on those under the age of 65 who have a commercial insurer listed as either their primary or secondary payer. Because most kidney patients in our sample are part of the Medicare ESRD program, the ability to observe secondary payer is a key feature of our data that allow us to conduct this analysis. As in the above median Black analysis, we find significantly larger effects on transplant counts and statistically indistinguishable increases in the transplant rate between White and Black patients. While gaps remain, when comparing White and Black patients of similar payer status, the gains from innovation are more evenly distributed. Appendix Table 7 presents results on all behaviors and outcomes for this subgroup.

Finally, we explore the possibility that racial concordance explains our findings. While prior research has not identified improved outcomes for same race donor/recipient pairs relative to mixed donor/recipient pairs, the higher likelihood of biological compatibility within race groups may still affect organ matching. For instance, if the HCV^+ patients who benefited from DAAs were disproportionately White and would have received livers from White donors in the absence of DAAs, then the organs effectively freed up by DAAs would more often come from White donors. As a result, those livers may have been easier to match with other White recipients, contributing to the larger gains we observe among White HCV^- ESLD patients. Instead, in Appendix Table 8, we show no effect of DAAs on the shares of White or Black deceased donors, even in areas with above median numbers of Black patients. As a result, we rule out racial concordance as a mechanism driving our results.

6 Conclusion

This research addresses the broad question of how the gains from medical innovation are distributed across race. In the context of a curative technology for the leading cause of infectious disease death in the U.S., we study the racial incidence of the indirect benefits of this technology among patients in need of liver transplantation. We have three main conclusions. First, DAAs caused a disproportionate increase in transplants for White HCV^- ESLD patients. Second, despite a fairly algorithmic allocation mechanism for donor livers based on medical need, we show that patient resources (in this case, commercial insurance status) play a significant role in determining who gains access to newly freed resources. Finally, gaps in the gains to innovation are attenuated in areas with larger populations of Black patients and among those with private insurance. Our results imply that achieving equity in

the liver transplant market may require incorporating patient resources and patient geography into the allocation mechanism.

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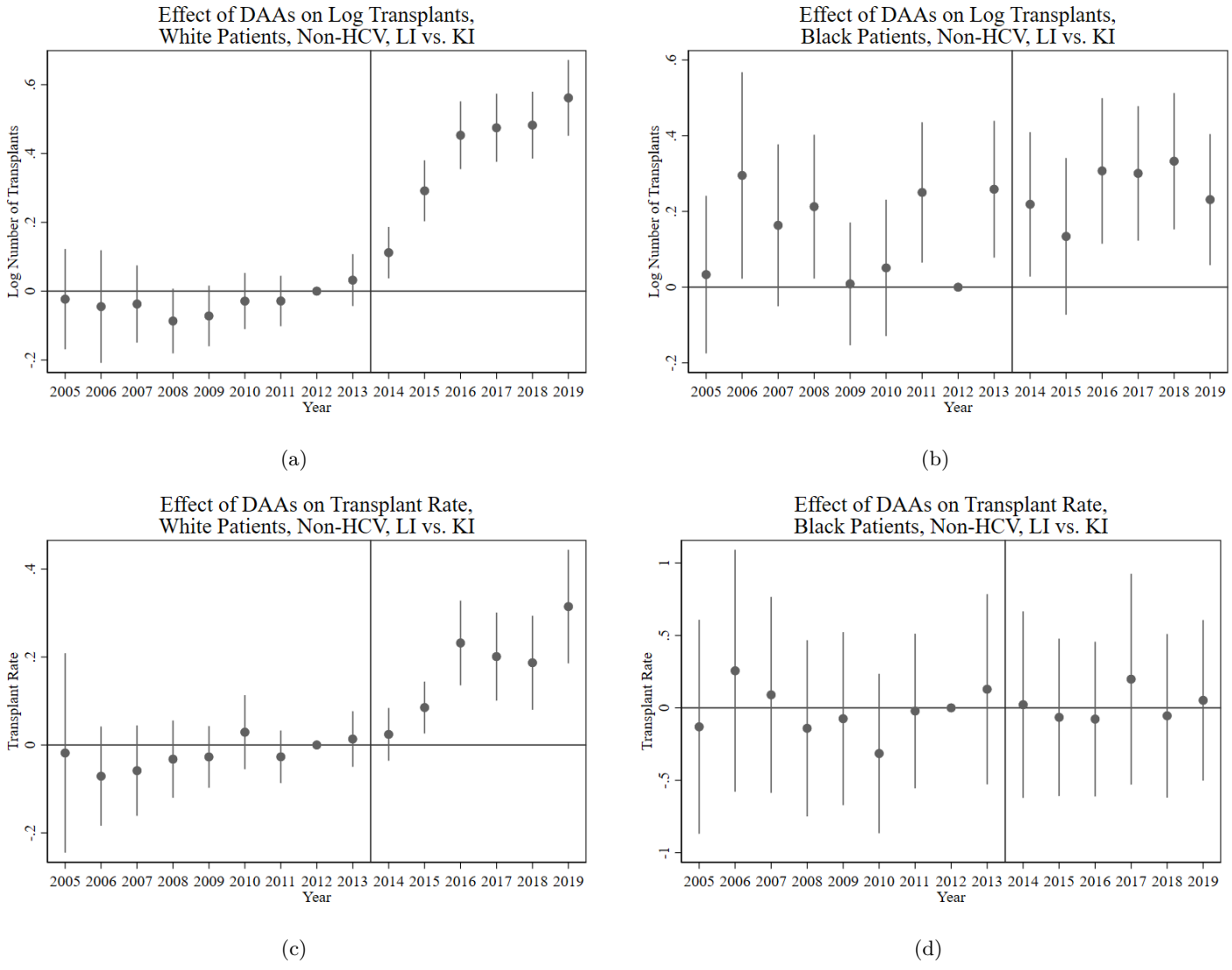
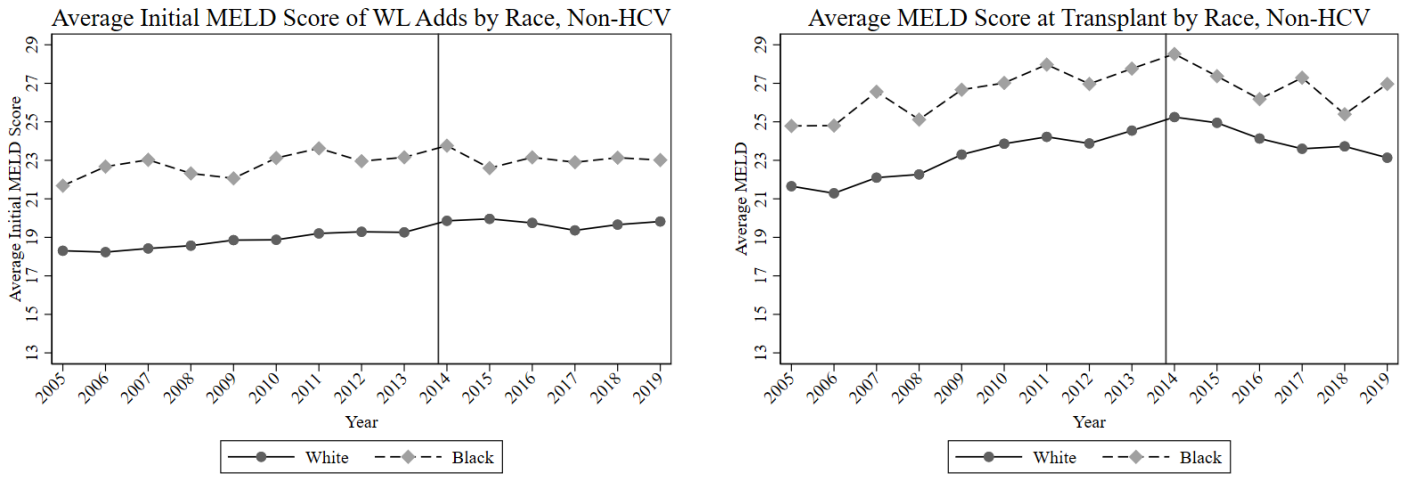
Figures and Tables

Figure 1: Transplant and Transplant Rate Event Studies by Race



Notes: Event studies of the count of transplants and the transplant rate by race relative to the normalization of 2012. Figures a. and b. are generated from Poisson regressions. The transplant rate is defined as the total number of transplants in a DSA/year divided by average number of registrations on the waiting list throughout that DSA/year. Vertical bars represent 95% confidence intervals.

Figure 2: Average MELD Score by Race



(a) (b)

Notes: Authors' calculations of yearly averages using SRTR data. The Model for End Stage Liver Disease (MELD) score is a measure of liver health and is predictive of short-term survival. Higher values indicate worse health.

Table 1: Liver Waiting List and Transplant Summary Statistics

	HCV+ Liver		HCV- Liver		Kidney	
	2005-13	2014-19	2005-13	2014-19	2005-13	2014-19
White						
WL Additions, Yearly	2,701	1,580	3,832	5,682	15,830	16,049
ESLD or ESRD Deaths, Yearly	10,511	10,204	65,837	60,245	34,953	36,016
WL Adds / Deaths	0.265	0.144	0.064	0.077	0.453	0.446
MELD at WL	16.2	15.6	18.8	19.7	-	-
MELD at TX	20.8	18.5	23.0	24.1	-	-
Days to TX	303	341	239	216	514	608
Transplants, Yearly	1,473	1,049	2,058	3,385	8,323	8,743
TX Rate	0.315	0.388	0.322	0.503	0.256	0.227
Black						
WL Additions, Yearly	433	336	365	499	9,623	10,736
ESLD or ESRD Deaths, Yearly	2,886	3,230	9,368	10,914	8,382	9,365
WL Adds / Deaths	0.150	0.104	0.039	0.046	1.148	1.146
MELD at WL	18.7	17.1	22.7	23.1	-	-
MELD at TX	22.5	19.8	26.4	27.0	-	-
Days to TX	220	269	201	192	864	879
Transplants, Yearly	253	218	220	317	3,973	5,118
TX Rate	0.487	0.491	0.452	0.601	0.137	0.145

Notes: Authors' calculations of endogenous variables by HCV^+ status and time period. Each statistic represents the annual average mean/count within the corresponding time period. Those for whom HCV status cannot be inferred are excluded from the calculations in this table. This amounts to roughly 15% of liver registrants, or 24,847 of 167,888 total liver registrants who listed between 2005 to 2019. Higher MELD scores reflects higher mortality risk. The transplant rate reflects the total number of transplants divided by average number of registrations on the waiting list throughout a given year.

Table 2: Difference-in-Differences Estimates

	HCV^+	HCV^-			
	TX	WL Additions	TX	Days to TX	TX Rate
	Poisson	Poisson	Poisson	Poisson	Fraction, OLS
DAA x White	-0.3886***	0.3803***	0.4486***	-0.2697***	0.1953***
	(0.0495)	(0.0487)	(0.0469)	(0.0513)	(0.0435)
	32.74	85.15	45.72	250.34	0.496
DAA x Black	-0.4003***	0.2021***	0.1106**	0.0323	0.0360
	(0.0831)	(0.0683)	(0.0558)	(0.1507)	(0.0763)
	5.62	8.12	4.89	212.26	0.809
Observations	5,655	5,700	5,700	5,190	5,567
N of Clusters	95	95	95	95	95

Notes: Each column of coefficients comes from a poisson regression of the outcome of interest on the DAA treatment indicator interacted with racial group, comparing group-specific liver counts to group-specific kidney counts. Note that all coefficients in this table except for the final column represent log point changes, which can be transformed into percentages using the formula $100 \times (e^{\hat{\beta}} - 1)$. Group-specific baseline means of the dependent variable reflect the pre-treatment period (2005–2013) DSA-year means in levels for HCV^- liver candidates only. While there are 57 DSAs in the U.S., we use modified DSA identifiers due to changes in DSA existence and services over time, which yields 50 kidney-serving DSA and 45 liver-serving DSA identifiers. Standard errors are in parentheses and are clustered at the DSA-by-organ level. *** p<0.01, ** p<0.05, * p<0.1

Table 3: Subsample Estimates

	Above Median Black DSAs		Above Median White DSAs		Any Private Payer, Under 65	
	Ln(Tx)	Tx Rate	Ln(Tx)	Tx Rate	Ln(Tx)	Tx Rate
DAA x White	0.5109***	0.1626**	0.3725***	0.1616**	0.4926***	0.2166***
	(0.0581)	(0.0653)	(0.0645)	(0.0673)	(0.0460)	(0.0445)
	53.54	0.577	41.36	0.531	29.96	0.494
DAA x Black	0.1628**	0.1085*	-0.1020	-0.0980	0.2345***	0.1640
	(0.0644)	(0.0635)	(0.1210)	(0.1403)	(0.0593)	(0.1810)
	7.94	0.695	2.23	1.010	2.84	0.878
Observations	2,820	2,773	2,880	2,787	5,685	5,424
N of Clusters	47	47	48	48	95	95

Notes: Each column of coefficients comes from a poisson regression of the outcome of interest on the DAA treatment indicator interacted with racial/ethnic group, comparing group-specific liver counts to group-specific kidney counts. Note that all coefficients in this table except for the final column represent log point changes, which can be transformed into percentages using the formula $100 \times (e^{\hat{\beta}} - 1)$. Group-specific baseline means of the dependent variable reflect the pre-treatment period (2005–2013) DSA-year means in levels for HCV^{-} liver candidates only. Above-median Black/White DSAs are designated based on the racial composition of candidates removed from the waiting list between 2005-13. While there are 57 DSAs in the U.S., we use modified DSA identifiers due to changes in DSA existence and services over time, which yields 50 kidney-serving DSA and 45 liver-serving DSA identifiers. Standard errors are in parentheses and are clustered at the DSA-by-organ level. *** p<0.01, ** p<0.05, * p<0.1