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ORIGINAL ARTICLE

Logistical burden of offers and allocation inefficiency in circle-based liver allocation

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Abstract

Recent changes to liver allocation replaced donor service areas with circles as the geographic unit of allocation. Circle-based allocation might increase the number of transplantation centers and candidates required to place a liver, thereby increasing the logistical burden of making and responding to offers on organ procurement organizations and transplantation centers. Circle-based allocation might also increase distribution time and cold ischemia time (CIT), particularly in densely populated areas of the country, thereby decreasing allocation efficiency. Using Scientific Registry of Transplant Recipient data from 2019 to 2021, we evaluated the number of transplantation centers and candidates required to place livers in the precircles and postcircles eras, nationally and by donor region. Compared with the precircles era, livers were offered to more candidates (5 vs. 9; $p < 0.001$) and centers (3 vs. 5; $p < 0.001$) before being accepted; more centers were involved in the match run by offer number 50 (9 vs. 14; $p < 0.001$); CIT increased by 0.2 h (5.9 h vs. 6.1 h; $p < 0.001$); and distribution time increased by 2.0 h (30.6 h vs. 32.6 h; $p < 0.001$). Increased burden varied geographically by donor region; livers recovered in Region 9 were offered to many more candidates (4 vs. 12; $p < 0.001$) and centers (3 vs. 8; $p < 0.001$) before being accepted, resulting in the largest increase in CIT (5.4 h vs. 6.0 h; $p < 0.001$). Circle-based allocation is associated with increased logistical burdens that are geographically heterogeneous. Continuous distribution systems will have to be carefully designed to avoid exacerbating this problem.

Abbreviations: CIT, cold ischemia time; COVID-19, coronavirus disease 2019; DBD, donation after brain death; DSA, donor service area; HHRI, Hennepin Healthcare Research Institute; HRSA, Health Resources and Services Administration; NM, nautical miles; OPO, organ procurement organization; OPTN, Organ Procurement and Transplantation Network; SRTR, Scientific Registry of Transplant Recipients; UNOS, United Network for Organ Sharing.

INTRODUCTION

Persistent geographic disparities in liver allocation[1] based on donor service areas (DSAs) led the Organ Procurement and Transplantation Network (OPTN) to replace DSA-based allocation with circle-based allocation. On February 4, 2020, deceased donor liver allocation transitioned to the acuity circles allocation system, which uses three concentric circles of increasing radius around the donor hospital—150, 250, and 500 nautical miles (NM).[1–3] Replacing DSAs with circles as the geographic unit of allocation may increase the logistical burden on transplantation centers and organ procurement organizations (OPOs).

Working relationships between transplantation centers and OPOs naturally arose based on a shared DSA. Replacing DSAs with circles may increase the complexity of the allocation system by increasing the number of necessary relationships between transplantation centers and OPOs.[4,5] This increased complexity might increase the number of transplantation centers and candidates who receive an offer prior to liver placement, thereby decreasing allocation efficiency by increasing distribution time and cold ischemia time (CIT). Changes in complexity likely differ depending on donor quality. Donation after circulatory death, or donation after brain death (DBD) and donor age of at least 70 years (hereafter referred to as “marginal” donors), are primarily allocated within only the 150 NM circle, whereas DBD donors less than 70 years old (hereafter referred to as “nonmarginal” donors) are primarily allocated within all three circles, up to 500 NM.

Using Scientific Registry of Transplant Recipient (SRTR) data, we quantified the change in logistical burden due to circle-based liver allocation. We compared the number of transplantation centers and candidates required to place a liver, CIT, and distribution time before and after circles. Finally, we stratified all of these analyses by donor quality to determine the impact of allocation sequence and by OPTN region to determine the impact of geography on logistical burden.

MATERALS AND METHODS

Data source

This study used data from the SRTR. The SRTR data system includes data on all donors, waitlisted candidates, and transplantation recipients in the United States, submitted by the members of the OPTN, and has been described elsewhere.[6] The Health Resources and Services Administration (HRSA), US Department of Health and Human Services, provides oversight of the activities of the OPTN and SRTR contractors.

TABLE 1 Increased burden associated with circle-based liver allocation

	After circles	Before circles	*p* value
Offer number at acceptance	5	9	< 0.001
Center number at acceptance	3	5	< 0.001
Center number at offer 50	9	14	< 0.001
CIT, h	5.9	6.1	< 0.001
Distribution time, h	30.6	32.6	< 0.001

Note: Distribution time is defined as the duration from the match run submit date to organ reperfusion, where organ reperfusion was estimated as the time at cross clamp plus ischemia time.
Abbreviation: CIT, cold ischemia time.

Study population and analysis

We studied match run and transplantation data for all deceased donor livers from February 4, 2019, to February 4, 2021. The precircles era was defined as February 4, 2019, to February 4, 2020, and the postcircles era was defined as February 4, 2020, to February 4, 2021. Within a match run, we defined the center number at offer x as the number of unique transplantation centers that had at least one candidate on the match run with offer number $\leq x$. For each match run with at least one bypassed offer, we removed all bypassed offers and renumbered the offer and center number throughout the match run, unless all offers were bypassed until an accepted offer, in which case that match run was removed. When considering offer and center number at acceptance, we only considered accepted offers that ultimately resulted in transplantation.

We defined distribution time as the duration from the match run submission to organ reperfusion, where organ reperfusion was estimated as the time at cross clamp plus ischemia time. Ischemia time was defined as CIT, plus warm ischemia time when reported. Median values before and after circles were compared using the two-sided permutation test, and mean values before and after circles were compared using the two-sided *t* test.

RESULTS

Match run analysis

With circle-based liver allocation, the median offer number at acceptance increased (5 vs. 9; $p < 0.001$), the median center number at acceptance increased (3 vs. 5; $p < 0.001$), and the median center number at offer number 50 on the match run increased (9 vs. 14; $p < 0.001$; Table 1). These increases were driven primarily by nonmarginal donors (Table 2). Stratifying by donor region, median offer number at acceptance did

TABLE 2 Increased burden associated with circle-based liver allocation based on donor quality

	Nonmarginal donors After circles	Before circles	*p* value	Marginal donors After circles	Before circles	*p* value
Offer number at acceptance	5	8	< 0.001	12	15	0.07
Center number at acceptance	5	8	< 0.001	12	15	0.06
Center number at offer 50	9	17	< 0.001	7	7	> 0.99
CIT, h	6.0	6.1	< 0.001	5.6	5.6	0.62
Distribution time, h	31.6	33.7	< 0.001	23.9	25.5	0.006

Note: Marginal donors are donation after circulatory death, or DBD and donor age of at least 70 years. Nonmarginal donors are DBD and donor age less than 70 years. Abbreviations: CIT, cold ischemia time; DBD, donation after brain death.

not change in Regions 4 (7 vs. 8; $p = 0.44$), 5 (7 vs. 6; $p = 0.75$), or 6 (4 vs. 5; $p = 0.63$) but increased in every other region, with the greatest increase being in Region 9 (4 vs. 12; $p < 0.001$; Figure 1). Median center number at acceptance did not change in Regions 3 (3 vs. 4; $p = 0.20$), 5 (4 vs. 4; $p > 0.99$), or 6 (2 vs. 3; $p = 0.11$) but increased in every other region, with the greatest increase being in Regions 2 (4 vs. 9; $p < 0.001$), 9 (4 vs. 8; $p < 0.001$), 10 (2 vs. 7; $p < 0.001$), and 11 (2 vs. 7; $p < 0.001$; Figure 2). Median center number at offer number 50 on the match run did not change in Regions 5 (8 vs. 9; $p = 0.06$) or 6 (5 vs. 6; $p = 0.77$) but increased in every other region, with the greatest increase being in Region 9 (7 vs. 19; $p < 0.001$; Figure 3).

Cold ischemia time and distribution time analysis

With circle-based liver allocation, the mean CIT increased by 0.2 h (5.9 h vs. 6.1 h; $p < 0.001$) (Table 1). Mean CIT increased by 0.1 h for nonmarginal donors (6.0 vs. 6.1; $p < 0.001$) but did not increase for marginal donors (5.6 vs. 5.6; $p = 0.62$; Table 2). Stratifying by donor region, mean CIT did not change for donor livers recovered in Regions 2, 3, 4, 5, 6, or 7, but increased in Regions 1 (5.7 h vs. 6.3 h; $p < 0.001$), 8 (5.5 h vs. 5.9 h; $p = 0.001$), 9 (5.4 h vs. 6.0 h; $p < 0.001$), 10 (5.4 h vs. 5.8 h; $p < 0.001$), and 11 (5.5 h vs. 6.0 h; $p < 0.001$; Figure 4).

Mean distribution time, that is, the duration between the match run submission and organ reperfusion, increased by 2.0 h (30.6 h vs. 32.6 h; $p < 0.001$; Table 1). Mean distribution time increased by 2.1 h for nonmarginal donors (31.6 vs. 33.7; $p < 0.001$) and increased by 1.6 h for marginal donors (23.9 vs. 25.5; $p = 0.006$; Table 2). Stratifying by donor region, there was no significant change in mean distribution time in Regions 4, 6, or 7. Mean distribution time increased in every other region, with the greatest increase being in Regions 1 (27.4 h vs. 31.3 h; $p < 0.001$) and 9 (29.4 h vs. 33.2 h; $p < 0.001$; Figure 5).

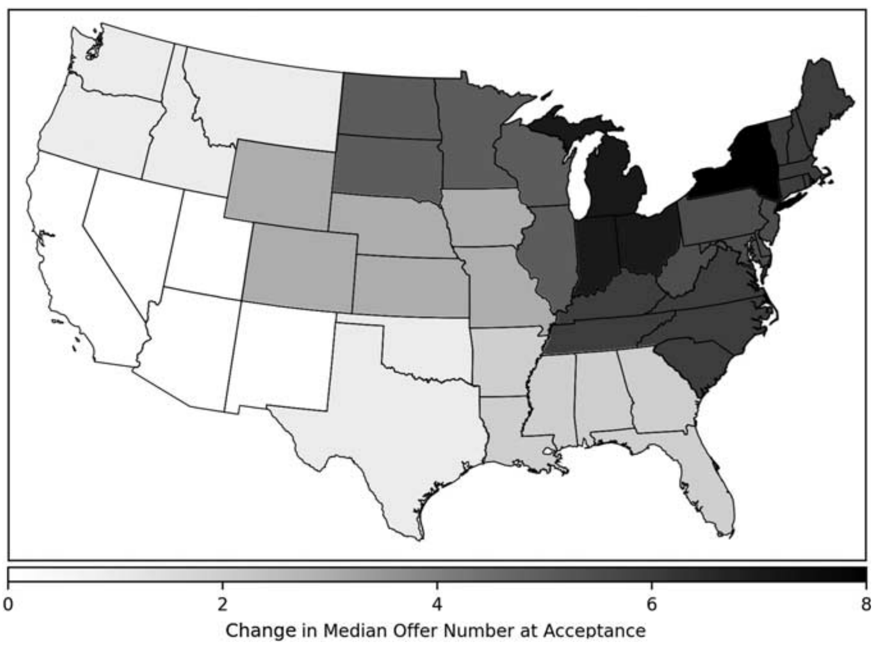

FIGURE 1 Geographic variation of the change in median offer number at acceptance after the implementation of circle-based liver allocation

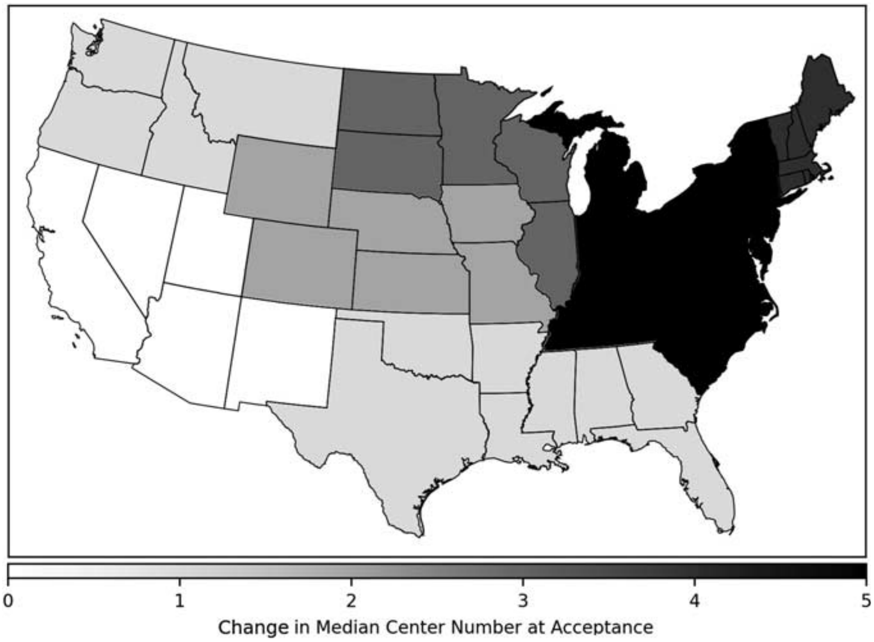

FIGURE 2 Geographic variation of the change in median center number at acceptance after the implementation of circle-based liver allocation

DISCUSSION

In this national study of the liver transplantation waiting list, we found that circle-based liver allocation is associated with increased logistical burdens, as evidenced by an increase in the number of transplantation centers and candidates responding to offers before liver acceptance. Increased logistical burdens primarily impacted nonmarginal donors (i.e., DBD donors <70 years old), which are offered more broadly than marginal donors. These burdens varied greatly by donor region. In general, logistical burden increased the most for livers recovered in the East and the least for livers recovered in the West. This is because centers are more densely located in the East, and because the circles are larger than United Network for Organ Sharing (UNOS) regions and DSAs in the East, while circles are not larger than many UNOS regions and DSAs in the West (Figure 6). Circle-based liver allocation is also associated with increased mean

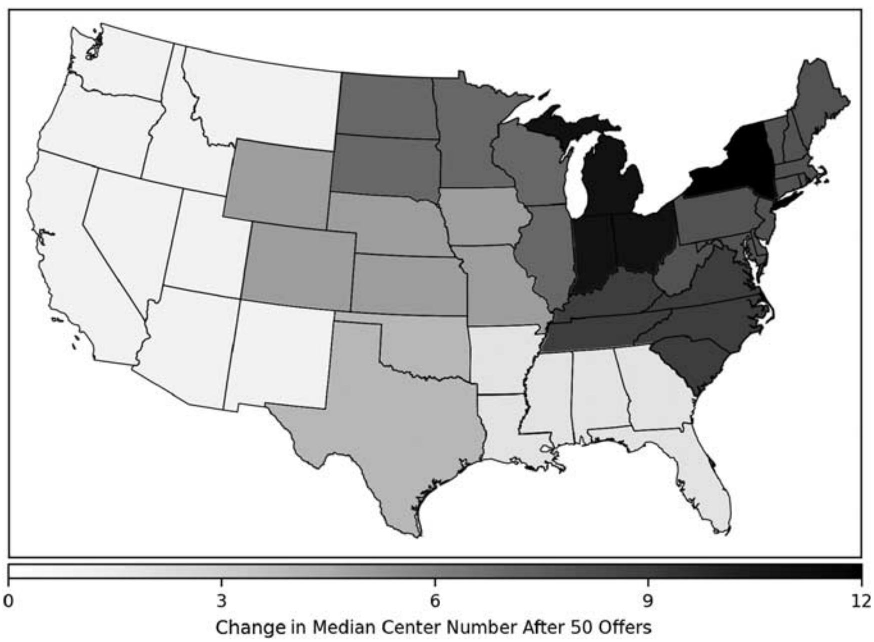

FIGURE 3 Geographic variation of the change in median center number at offer number 50 on the match run after the implementation of circle-based liver allocation

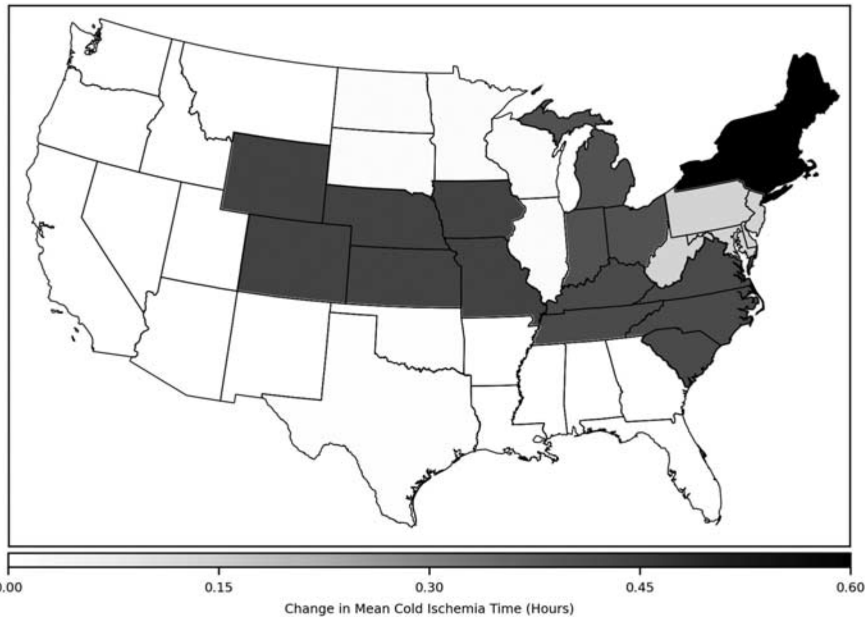

FIGURE 4 Geographic variation of the change in mean CIT after the implementation of circle-based liver allocation

distribution time, that is, the duration between match run submission and organ reperfusion. Mean distribution time increased by 2.0 h, although mean CIT increased only very slightly by 0.2 h, most likely because livers are usually allocated before being recovered. These increases in delays similarly varied greatly by donor region.

Circle-based liver allocation increased liver transplantation rates for higher Model for End-Stage Liver Disease candidates,[7] thereby better aligning liver allocation with the Final Rule by deemphasizing the candidate's place of listing. The Final Rule states that allocation systems "shall not be based on the candidate's place of residence or listing", except to the extent required by other competing interests, among which is to "promote the efficient management of organ placement".[8] Our work suggests that the liver allocation system has become less efficient by requiring more transplantation centers and candidates to place an organ.

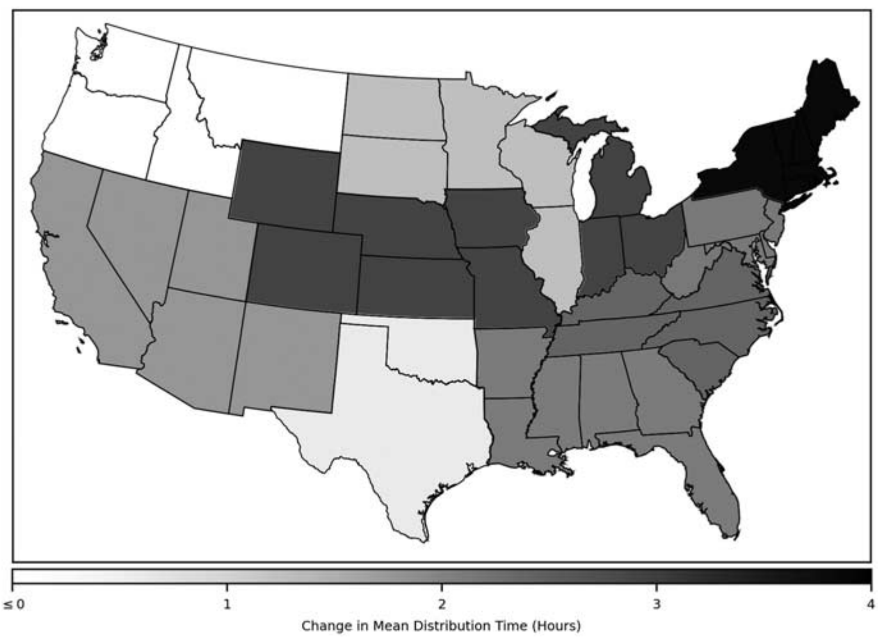

FIGURE 5 Geographic variation of the change in mean distribution time after the implementation of circle-based liver allocation. Distribution time was defined as the duration from the match run submission to organ reperfusion, where organ reperfusion was estimated as the time at cross clamp plus ischemia time

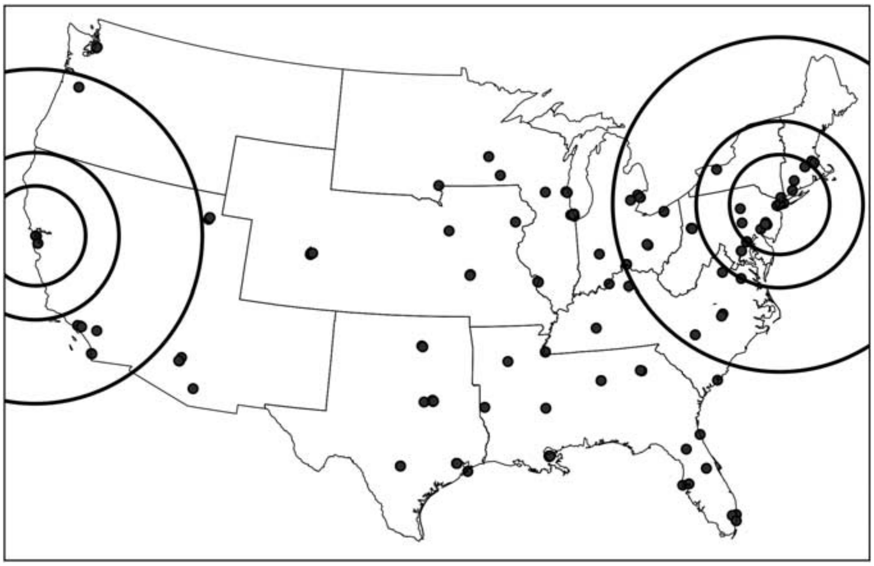

FIGURE 6 Geographic heterogeneity in liver transplantation. Each dot represents a liver transplantation program, with United Network for Organ Sharing regional boundaries drawn. The three circles used by acuity circles (150, 250, and 500 NM) are drawn around San Francisco, CA and New York, NY. Transplantation center density is much higher in the East compared with the West, and regions in the East are small compared with the circle sizes, whereas regions in the West are large compared with the circle sizes

Our results have implications for the development of continuous distribution systems of allocation.[9] Circle-based allocation, like DSA-based allocation, uses hard geographic boundaries. Continuous distribution, by contrast, has no hard geographic boundaries. Under continuous distribution, a candidate at *any* transplantation center could, in principle, be ranked high on the match run regardless of his place of listing or the location of donor recovery. Depending on how geography is weighted alongside other competing interests, changes in burden could decrease, remain constant, or increase. Before implementing any proposed continuous distribution system, policymakers could look at the median center number by offer number 50, as we have done, and compare it to circle-based allocation to estimate the potential increase in burden. For example, by limiting allocation of marginal donors to 150 NM, acuity circles did not increase the center number at offer 50 compared with DSA-based allocation for those donors. The median center number by offer 50 is a complexity metric that is independent of center accept/decline decisions, and therefore it can be calculated prior to implementing a new policy.

Circle-based allocation systems, like previous OPTN policies, were chosen ad hoc from a set of plausibly reasonable policies. By contrast, an optimization perspective[10–12] could mean applying computational tools to design continuous allocation scores that maximize transplantation benefits while enforcing constraints, say, that logistical complexity does not increase too much and that organs are distributed equitably. Furthermore, because increased burden varies greatly by geography, an optimization approach could be used to design a geographically heterogeneous continuous allocation score.[13,14]

Circle-based liver allocation is associated with a national increase of 2.0 h in mean distribution time. This delay in allocation is likely a delay in organ placement due to the increased number of centers required to place an organ. Another possible source of delay would be travel delays due to broader sharing. Sheetz and Waits[15] found in a short-term study that acuity circles more than doubled the median travel distance for livers and OPTN regions exported 344% more livers, and Chyou et al.[16] found that the proportion of liver transplants transported across a flight-consistent distance increased under acuity circles. Travel has increased under acuity circles and this adds to the burdens on transplantation centers and OPOs; however, increased travel has not meaningfully impacted mean CIT. Mean CIT increased nationally by only 0.2 h, ranging from no change to an increase of 0.6 h depending on donor region.

The increased number of centers required to respond to each offered organ increases resource and personnel burden on transplantation centers and OPOs. For example, Wall et al. showed an increased cost per both accepted *and* declined livers under acuity circles allocation.[17,18] Our estimates for the burden of making and evaluating offers are likely underestimated because transplantation centers that regularly evaluate offers before becoming primary would have evaluated additional offers beyond those accounted for here.

The implementation of circles in liver allocation overlaps almost entirely with the coronavirus disease

2019 (COVID-19) pandemic, making it difficult to distinguish the effect of the policy from effects of the pandemic. This is especially true regarding offer number at acceptance, center number at acceptance, CIT, and distribution time. Offer acceptance behavior likely changed in response to changes in allocation policy and in response to the introduction of the pandemic. Similarly, increased CIT is associated with worse posttransplantation outcomes,[19,20] but it would be difficult to distinguish worse outcomes due to increased CIT from those due to COVID-19. By contrast, center number at offer number 50 on the match run is not affected by accept/decline decisions or COVID-19 and therefore provides independent evidence that circle-based liver allocation has increased the complexity of the liver allocation system.

Circle-based liver allocation increased the number of transplantation centers and candidates responding to offers before acceptance. In addition, circle-based liver allocation is associated with an increase in mean CIT and distribution time. We encourage the OPTN to attend to the logistical complexity of match runs in moving toward continuous distribution systems, perhaps by using optimization and design approaches to limit complexity while simultaneously reducing geographic disparity.

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CONFLICT OF INTEREST

Nothing to report.

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REFERENCES

1. Salvalaggio PR. Geographic disparities in transplantation. Curr Opin Organ Transplant. 2021;26:547–53.
2. Aby ES, Lake JR. Basic principles of liver allocation and development over the years. Curr Opin Organ Transplant. 2020;25:99–103.
3. Leventhal TM, Florek E, Chinnakotla S. Changes in liver allocation in United States. Curr Opin Organ Transplant. 2020;25:52–8.
4. Adler JT, Husain SA, King KL, Mohan S. Greater complexity and monitoring of the new kidney allocation system: implications and unintended consequences of concentric circle kidney allocation on network complexity. Am J Transplant. 2021;21:2007–13.
5. Wood NL, VanDerwerken DN, Segev DL, Gentry SE. Increased logistical burden in circle-based kidney allocation. Transplantation. 2022;84:S4–5.
6. Leppke S, Leighton T, Zaun D, Chen SC, Skeans M, Israni AK, et al. Scientific registry of transplant recipients: collecting, analyzing, and reporting data on transplantation in the United States. Transplant Rev (Orlando). 2013;27:50–6.
7. Wey A, Noreen S, Gentry S, Cafarella M, Trotter J, Salkowski N, et al. The effect of acuity circles on deceased donor transplant and offer rates across model for end-stage liver disease scores and exception statuses. Liver Transpl. 2021;28:363–375.
8. CFR 121.8(a)(8) allocation of organs. 2022 [cited 2022 Jan 29]. Available from: https://www.ecfr.gov/current/title-42/chapter-I/subchapter-K/part-121
9. Snyder JJ, Salkowski N, Wey A, Pyke J, Israni AK, Kasiske BL. Organ distribution without geographic boundaries: a possible framework for organ allocation. Am J Transplant. 2018;18:2635–40.
10. Bertsimas D, Papalexopoulos T, Trichakis N, Wang Y, Hirose R, Vagefi PA. Balancing efficiency and fairness in liver transplant access: tradeoff curves for the assessment of organ distribution policies. Transplantation. 2020;104:981–7.
11. Gentry S, Chow E, Massie A, Segev D. Gerrymandering for justice: redistricting U.S. liver allocation. Interfaces. 2015;45:462–80.
12. Gentry SE, Massie AB, Cheek SW, Lentine KL, Chow EH, Wickliffe CE, et al. Addressing geographic disparities in liver transplantation through redistricting: addressing geographic disparities: redistricting. Am J Transplant. 2013;13:2052–8.
13. Karami F, Kernodle AB, Ishaque T, Segev DL, Gentry SE. Allocating kidneys in optimized heterogeneous circles. Am J Transplant. 2021;21:1179–85.
14. Wood NL, Kernodle AB, Hartley AJ, Segev DL, Gentry SE. Heterogeneous circles for liver allocation. Hepatology. 2021;74:312–21.
15. Sheetz KH, Waits SA. Outcome of a change in allocation of livers for transplant in the United States. JAMA Surg. 2021;156:496–8.

16. Chyou D, Karp S, Shah MB, Lynch R, Goldberg DS. A 6-month report on the impact of the organ procurement and transplantation network/united network for organ sharing acuity circles policy change. Liver Transpl. 2021;27:756–9.
17. Wall AE, da Graca B, Asrani SK, Ruiz R, Fernandez H, Gupta A, et al. Cost analysis of liver acquisition fees before and after acuity circle policy implementation. JAMA Surg. 2021;156:1051–7.
18. Karp SJ. Acuity circles—higher cost for fewer transplants? JAMA Surg. 2021;156:1058.
19. Paterno F, Guarrera JV, Wima K, Diwan T, Cuffy MC, Anwar N, et al. Clinical implications of donor warm and cold ischemia time in donor after circulatory death liver transplantation. Liver Transpl. 2019;25:1342–52.
20. Segev DL, Kucirka LM, Nguyen GC, Cameron AM, Locke JE, Simpkins CE, et al. Effect modification in liver allografts with prolonged cold ischemic time. Am J Transplant. 2008;8:658–66.

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