Paying It Backward and Forward: Expanding Access to Convalescent Plasma Therapy Through Market Design

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Abstract

COVID-19 convalescent plasma (CCP) therapy is currently a leading treatment for COVID-19. At present, there is a shortage of CCP relative to demand. We develop and analyze a model of centralized CCP allocation that incorporates both donation and distribution. In order to increase CCP supply, we introduce a mechanism that utilizes two incentive schemes, respectively based on principles of \paying it backward" and \paying it forward." Under the rst scheme, CCP donors obtain treatment vouchers that can be transferred to patients of their choosing. Under

1 Introduction

Without therapeutic agents or vaccines for the novel coronavirus disease, COVID-19, the medical community hor7.0490(an[1 71vinfectd-1v)76-pati7(for)-[1 71vreceivforcoromy0forfordiseaserco59-337(med.)

states: \practically every day, another medical center announces plans to begin administering convalescent plasma to patients with COVID-19." Blood donation centers such as those at the American Red Cross are being repurposed to collect CCP; at time of writing, more than 2,000 sites can accept plasma donations, and the Mayo Clinic has been named the lead institution in the U.S. to oversee the FDA's expanded CCP access system.

By and large, access to CCP is uncoordinated. Donation efforts have thus far been based on outreach from physicians, hospitals, and local public health authorities.[6] Current disparities in CCP access depend on regional differences, socio-economic status, social-media appeals, and physician behavior (see, e.g., Aleccia, 2020). Harrison (2020) has emphasized the need for clear criteria for plasma allocation, so that the de facto allocation does not reduce to one based on awarding units to patients whose advocates \yell at hospital services the most."

The absence of transparent and well-defined CCP allocation rules has important equity implications due to both blood type differences across ethnic groups and variation in COVID-19 exposure and testing driven by differences in socioeconomic status and health care access.[7]

This paper introduces and analyzes a market design approach to collecting and distributing CCP. We develop a steady-state continuum model that jointly incorporates donation and allocation of CCP. The crux of our mechanism is systematic utilization of dual *pay-it-backward* and *pay-it-forward* principles to increase the supply of CCP. Through the pay-it-backward principle, the system \pays back" a CCP donor for her potentially life-saving donation by giving her a number of vouchers that can be used to obtain priority for CCP therapys of her loved ones should the need arise. Through the pay-it-forward principle, a patient receives priority access for CCP therapy in exchange for a pledge to return the favor back by donating her own CCP in the near future, assuming she recovers and becomes eligible for plasma donation.[8] These features embed and formalize practices that are already informally embraced by some doctors in their attempt to increase the recruitment of CCP donors. For example, a pulmonologist interviewed in *JAMA* explained (Rubin, 2020):

> \. . . blood collection centers generally do not permit donors to designate their blood for a specific patient. Instead, Brown said, she encourages people interested in making a designated donation to pay it forward and donate to replace the convalescent plasma used by their intended recipient."

In our steady-state model of plasma donation, CCP donors may be given priority vouchers that can be used to give treatment priority to family members and other close associates; priority is also given to participants in clinical trials. The steady-state availability of CCP therapy is a function of

[6] There have also been several heart-wrenching appeals for CCP from family and friends of patients, often via the internet and through groups like Survivor Corps (see, e.g., Burch and Harmon, 2020).

[7] Kidney allocation policy has faced similar equity concerns. African-Americans make up a disproportionate share of renal failure patients of blood types O and B (Rettner, 2019), and the waiting times for kidneys with these two blood types are considerably higher than the waiting times for kidneys of blood types A and AB. In 2018, the numbers of deceased-donor transplants per 100 waitlist years for blood types O and B were roughly half the number for AB (OPTN, 2018, Figure KI 18).

[8] A similar feature exists in non-directed donor (NDD) chains in kidney exchange, where a patient receives a living-donor kidney before her incompatible donor donates a kidney to a patient in another incompatible patient-donor pair. Such an NDD chain becomes possible with the undirected initial donation of a Good Samaritan donor; the longest single-center paired kidney exchange of this form involved 101 donors and recipients (Pope, 2018).

the number of patients who have recovered (both through CCP therapy and by other means). We find that so long as the CCP replenishment rate is large enough to support the clinical trial, it is possible to treat all prioritized patients in equilibrium. The rate of treatment for non-prioritized patients becomes higher, as well. We characterize when it is possible to treat all patients|even those who are not ex ante prioritized|and show that so long as recovered patients are more willing to donate if they receive vouchers, introducing a voucher system strictly benefits non-prioritized patients. Overall treatment availability expands further if we prioritize patients who pledge to pay it forward by donating CCP once they have recovered: if patients who pledge to donate have an aggregate CCP replenishment rate that is more than one-for-one, prioritizing those patients increases the treatment rate for non-prioritized patients, irrespective of how many patients make pledge to donate ex ante. Most of our analysis works with a single blood type for ease of illustration. But we show how to combine that analysis with ideas from graph theory to identify the optimal cross-blood type CCP-pooling strategy to maximize an egalitarian treatment objective.

The remainder of this paper is structured as follows. Section 2 reviews some design considerations that might be relevant for practical implementation of our idea. Section 3 describes our model of plasma donation and distribution, specialized to the case of only one blood type. Section 4 examines the possibility of pooling multiple blood types, and reviews related literature. Section 5 concludes.

2 Market Design Considerations for Plasma Donation and Distribution

We envision a mechanism where only a portion of the CCP supply can be allocated through the two types of incentive schemes we introduce. We refer to that portion as the *incentivized CCP reserve*. The remaining portion is reserved for participants of clinical trials, as well as for any other patient group the central planner deems adequate; for simplicity, we refer to that portion as the *clinical trial CCP reserve*. The clinical trial CCP reserve is effectively exogenous|at any point in time, the clinical trial CCP reserve will be allocated to its beneficiaries.

The incentivized CCP reserve, meanwhile, is endogenous|depending on two different types of incentives. The first incentive we consider is the provision of a fixed number of vouchers to CCP donors, which can be later redeemed by patients of the donors' choosing; we refer to this as a *pay-it-backward* incentive. These vouchers are of potential value to donors, because patients who arrive the system with a voucher have *first-tier priority* access for units in the incentivized CCP reserve.

The second type of incentive|which we call a *pay-it-forward* incentive|exploits the unusual feature of the CCP therapy that any patient who recovers becomes a potential CCP donor. Since each donor can supply CCP that is sufficient for the treatment needs of 2-4 patients each donation up to three times, this provides a unique opportunity to expand access to CCP: if we can use CCP to increase the recovery rate, and those recovered patients go on to donate CCP, then we can grow the CCP supply more than one-for-one. Thus, we propose to provide *second-tier priority* access to units in the incentivized CCP reserve to patients who do not have a voucher but who pledge to donate CCP in the near future, in the event that they recover. Any patient who is able to materialize her pledge through a CCP donation may also receive a number of vouchers, although not the same number provided to

donors of pay-it-backward incentives.

The priority tiers for access to treatment through the incentivized CCP reserve are then as follows:

1. *First-tier priority*: Patients who arrive with vouchers that are obtained in either way.
2. *Second-tier priority*: Patients who arrive with no voucher but who pledge to donate CCP upon recovery, subject to passing eligibility requirements.
3. *Third-tier priority*: Any other patient who is in need of CCP therapy.

Within each tier, ties are broken in a systematic way determined by the central planner.

Meanwhile, the allocation process in the clinical trial CCP reserve is fully regulated by the central planner.

2.1 Pay-it-Backward Incentives

Some donors are purely altruistic and they do not need any incentive to donate. But potential donors may at least in part wish to be able to donate to their loved ones. For these donors, the pay-it-backward incentive can be expected to be valuable because the voucher provides a medium of exchange that eases three frictions associated with donation. For example, consider a potential donor who wants to donate to a family member. She may not be able to donate to her intended recipient if any of the following three di culties arise:

1. The donor and intended recipient are*time-incompatible*: by the point at which the bene ciary needs CCP, the donor is medically unable to donate.
2. The donor and intended recipient are*plasma incompatible*: the bene ciary has anti/F17 1586(the)-40

multiple units of plasma, the resulting increase in CCP supply bene ts the overall patient pool|not just voucher recipients.

There is a precedent for these types of vouchers in kidney exchange. A *voucher for a chronologically incompatible* pair (Veale et al. (2017)) involves giving a (typically young) patient priority for a future kidney transplant in exchange for a kidney donation from an older donor today; this mechanism is used when the donor is expected be too old to donate when the patient will need a transplant. A relatively modest number of these intertemporal exchanges have been organized by the National Kidney Registry, which arranges kidney chains initiated by good-samaritan donors.[9] We anticipate a potentially more substantial role for vouchers in CCP donation, because the risk and potential negative consequences to the donor are much lower under CCP donation than for kidney donation.

2.2 Pay-it-Forward Incentives

The pay-it-backward principle just discussed rewards CCP donation ex post. The pay-it-forward principle, by contrast, gives an ex ante reward for a pledge to donate in the future conditional on recovery and eligibility; as we show in the next section, this too can be expected to increase the overall CCP supply, so long as a large enough fraction of the pledged donations are actually carried through.

It is thus essential to think about how many pledged donations will actually materialize. Some patients who bene t from pay-it-forward incentives may turn out to be unable to donate for medical eligibility reasons.

It is also possible that a patient may simply decide not to honor her pledge. This is an impor(her)-32dc

2.3 Price-Based Covid-19 Convalescent Plasma Markets

There is an active debate in economics and philosophy on the appropriate role of market-based mechanisms with compensation for human products used in medicine or medical research like kidneys, blood, blood products, sperm, breast milk, bone marrow, and other tissues.[11] Since, as far as we know, there is no current market where infected patients can buy CCP or where recovered patients can sell CCP, we do not consider this possibility as part of our model.

We brie y comment on how a price-based market for CCP might relate to these prior debates. Non-regenerative human products such as kidneys are at one extreme. The 1984 National Organ Transplant Act (NOTA) states \it shall be unlawful for any person to knowingly acquire, receive or otherwise transfer any human organ for valuable consideration for use in human transplantation," and it is a near-universal norm that monetary compensation should play no role in kidney allocation. A 2007 amendment to NOTA, known as the Charlie W. Norwood Living Organ Donation Act, clari ed that the language \valuable consideration" does not apply to human organ paired donation. Currently, live kidney donations are from unpaid volunteers with designated recipients.[12]

Regenerative human products like bone marrow and blood are at the other extreme|at present, there is compensation for some voluntary donors. A 2011 9th Circuit Court of Appeals ruled that NOTA's ban on donor compensation does not apply to bone marrow. Meanwhile, for blood there is an active market, where in the US, patients pay $334 per unit of whole blood to hospitals. US plasma donors are typically paid per donation, and plasma is aggregated and divided into parts to be sold to hospitals and drug companies (Slonim, Wang, and Garbarino, 2014). While there can be compensation, a donor of blood or blood products typically cannot designate a recipient.

Because CCP is a form of plasma, a natural question is whether a compensated market for CCP will develop. In our model, there is no option to pay to receive CCP or be paid for donating CCP, but a donor can designate the voucher in our model to particular patient in need. As a result, our model of CCP falls between the two extremes described above. We expect that in a crisis moment, there is unlikely to be an active compensated market for CCP (even though it may be impossible to fully prohibit resale of vouchers). If a price-based market does develop, society may deem it unacceptable. Even for a well-developed human product like blood, World Health Organization guidelines recommend that countries have 100% of blood donations come from non-remunerated volunteers due to social and ethical concerns (Slonim, Wang, and Garbarino, 2014). Perhaps more importantly, if vouchers attain monetary value, a signi cant concern is that some individuals may have an incentive to become sick in order to sell their CCP post-recovery, which seems ethically unacceptable.

3 A Model of ABO-identical Plasma Donation and Demand

To formalize our conceptual intuitions about the interaction between plasma donation and treatment, we develop a simple steady-state model of CCP donation and demand. In this section, we assume that each patent receives CCP from a donor of the same blood type.

[11] Some references are Arrow (1972), Becker and Elias (2007), Benabou and Tirole (2006), Roth (2007), Sandel (2012), Satz (2012), and Titmuss (1970).

[12] There is an active literature in economics on kidney exchange beginning with Roth, Sonmez, and Unver (2004, 2005b, 2007).

3.1 Paying it Backward through Priority Vouchers

We consider a CCP rationing system that sets aside some units of CCP for clinical trial patients through a *clinical trial CCP reserve*; the rest of the CCP supply is available to be distributed through our incentive schemes through the *incentivized CCP reserve*.

We first consider a pay-it-backward incentive scheme: We suppose that each individual who donates CCP receives $v_X \geq 0$ *priority vouchers* that can be used to give treatment priority to a family member or other close associate[13].

The novel feature of this incentivized CCP reserve is that while the clinical trial CCP reserve capacity is set as an exogenous parameter, the incentivized CCP reserve capacity will be endogenously determined at steady state as a function of certain population parameters as well as the priority voucher scheme in place. In particular, the incentivized CCP reserve will prioritize patient groups in the following order:

1. patients who have vouchers (we refer to these patients as *voucher-prioritized*); then
2. patients who do not have a voucher (*non-prioritized*).

Within each group priority group, CCP therapy is allocated based on a well-defined rule such as a point system or a lottery.

We contrast this system with one in which no vouchers are provided|i.e., $v_X = 0$|in which, there is a set-aside reserve for clinical-trial patients and the rest of the CCP supply is rationed among the remaining patients, with all CCP being supplied through purely altruremas6onateoni

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We denote the service rates for clinical-trial patients, voucher-prioritized patients, and non-prioritized patients by s^t_X, s^v_X, and s^n_X respectively; these are the proportions of the respective populations that are treated with CCP. The ow rates of recovery for each type of patient are then $s^t_X\ {}^t_X$, $s^v_X\ {}^v_X$, and $s^n_X\ {}^n_X$.

CCP can only be supplied by recovered patients. The ow rate of patients who can potentially provide CCP thus has four components: $s^t_X\ {}^t_X$, $s^v_X\ {}^v_X$, and $s^n_X\ {}^n_X$|all described in the previous paragraph|as well as patients who have recovered without CCP therapy, with ow rate $!_X$. We assume that recovering clinical-trial patients, recovering non-prioritized patients, and recovering patients using alternative treatment models donate CCP at the same rate p_X. We also make a simplifying worst-case scenario assumption regarding voucher-prioritized patients: we assume that voucher-prioritized patients who recover do not donate CCP.[18]

Thus, the steady-state CCP therapy supply ow rate is endogenously determined by

$$_X = p_X(s^t_X\ {}^t_X + s^n_X\ {}^n_X + !_X)k; \tag{1}$$

where p_X

it is possible to ensure that all clinical-trial and voucher-prioritized patients receive CCP therapy, so that

$$s_X^t = 1 \qquad \textit{and} \qquad s_X^v = 1: \tag{4}$$

Proof. The total ow rate of patients who are prioritized is given as $^t_X + \ ^v_X$. To serve all of them, we need (4), i.e., that

$$_X \qquad ^t_X + \ ^v_X \tag{5}$$

Substituting in (1) and (2), we see that (5) is equivalent to

$$p_X(\ ^t_X + s_X^n\ ^n_X + \ !_X)(k \quad r_X) \qquad ^t_X \ () \qquad k \quad \frac{^t_X}{p_X(\ ^t_X + s_X^n\ ^n_X + \ !_X)} \qquad r_X:$$

In the worst-case scenario, the service rate for non-prioritized patients would be $s_X^n = 0$, yielding

$$k \quad \frac{^t_X}{p_X(\ ^t_X + \ !_X)} \qquad r_X$$

as a su cient condition for (5); this is precisely (3) since $^t_X = \ _X$ is the reserve size. □

We next turn our attention to the CCP therapy service rates s_X^n for non-prioritized patients, which takes the form

$$s_X^n = \quad _X \quad s_X^t\ ^t_X \quad s$$

Corollary 1. *So long as the CCP replenishment rate is large enough to support the clinical trial (i.e.,* (3) *holds), the ow recovery rate of non-prioritized patients,* $s_X^n \ _X^n + !_X$*, is weakly higher than the rate that would arise absent CCP donation,* $!_X$*, even when all CCP-clinical-trial patients and voucher-prioritized patients are treated ahead of non-prioritized patients.*

From (7), we compute that s_X^n 1 whenever

$$p_X \quad \frac{_X + \ _X^n}{(\ _X + \ _X^n + !_X)(k \quad r_X)}: \tag{8}$$

We thus nd:

Proposition 2. *Whenever* (8) *holds, it is possible to treat all patients | prioritized and non-prioritized | at steady-state. In particular, it is possible to treat all patients when replenishment rate is above replacement; that is, when*

$$p_X(k \quad r_X) \quad \frac{_X + \ _X^n}{_X + \ _X^n + !_X}:$$

3.1.1 Altruistic Donation vs. Incentivized Backward Donation

Additionally, we can think of p_X in terms of a supply curve $p_X(\ )$ that is strictly increasing and di erentiable as a function of the voucher redemption rate, r_X. Thus, $p_X(0)$ refers to the altruistic donation probability (which is what would arise without any incentive scheme involving prioritization through vouchers).

We make the following assumption:

Assumption 1. The replenishment rate $p_X(r_X)$ $(k \quad r_X)$ is strictly increasing at $r_X = 0$ (i.e., $p_X^0(0)k > p_X(0)$).

Assumption 1

Proposition 3. *Under Assumption*

patients who are not part of clinical trials, do not have vouchers, and have not pledged to donate, with a ow rate of $\hat{s}_X^n \hat{}_X^n + I_X$.

The total steady-state ow of CCP therapy is

prioritized patient groups can all be treated by CCP if

$$\hat{\lambda}_X \quad \hat{\lambda}_X^t + \hat{\lambda}_X^v + \hat{\lambda}_X^f \;()\; p_X(\hat{\lambda}_X^t + \hat{s}_X^n \hat{\lambda}_X^n + \; !_X)(k \quad r_X) + p_X^f \hat{\lambda}_X^f (k \quad r_X^f) \quad \hat{\lambda}_X^t + \hat{\lambda}_X^f : \tag{16}$$

To capture the minimum amount of CCP needed to treat all pledged patients, we consider the worst-case scenario in which no non-prioritized patients are treated, i.e. $\hat{s}_X^n = 0$. Then necessary and su cient conditions for (16) to be satis ed regardless of $\hat{\lambda}_X^f$ are

$$p_X(k \quad r_X) \quad \frac{\hat{\lambda}_X^t}{p_X(\hat{\lambda}_X^t + \; !_X)} \qquad \text{and} \qquad p_X^f(k \quad r_X^f) \quad 1: \tag{17}$$

Replacing $\hat{\lambda}_X^t$ with $\quad_X$ in (17), we obtain (14). □

The rst condition in (14) is the same condition as (3): The replenishment rate of the CCP obtained from initially non-pledged patients should be at least as large as is needed to support the clinical trial CCP reserve. The second condition in (14) requires that the replenishment rate of CCP obtained from pledged patients should at least cover those patients' own initial treatment in steady-state.

We now examine the CCP service rate for non-prioritized patients when (14) holds:

$$\hat{s}_X^n = \frac{\hat{\lambda}_X \quad \hat{s}_X^t \hat{\lambda}_X^t \quad \hat{s}_X^v \hat{\lambda}_X^v \quad \hat{s}_X^f \hat{\lambda}_X^f}{\hat{\lambda}_X^n}. \tag{18}$$

Expanding (18) assuming $\hat{s}_X^v = 1$, we nd that

$$\hat{s}_X^n = \frac{\left[p_X(\hat{s}_X^t \hat{\lambda}_X^t + \hat{s}_X^n \hat{\lambda}_X^n + \; !_X)(k \quad r_X) \quad \hat{s}_X^t \hat{\lambda}_X^t\right] + \left[p_X^f \hat{s}_X^f \hat{\lambda}_X^f (k \quad r_X^f) \quad \hat{s}_X^f \hat{\lambda}_X^f\right]}{\hat{\lambda}_X^n}. \tag{19}$$

Solving (19) for $\hat{s}_X^n$ (replacing $\hat{\lambda}_X^t = \quad_X$ and $\hat{s}_X^t = 1$), we see that, assuming the pay-it-backward voucher replenishment rate does not on its own lead to in nite excess supply of CPP (i.e. $p_X(1 \quad r_X) < 1$),

$$\hat{s}_X^n = \frac{!_X p_X(k \quad r_X) \quad \quad_X \; 1 \quad p_X(k \quad r_X) \; + p_X^f \hat{s}_X^f \hat{\lambda}_X^f \; k \quad r_X^f \quad \frac{1}{p_X^f}}{}$$

for each blood type X. Here, $_X$ is the *steady-state supply* of blood-type X CCP to be rationed to non-prioritized patients while $_X$ is the *steady-state demand* for CCP by non-prioritized blood-type X patients.

4.1 Pooling for Plasma Treatment

Whenever, $_X < 0$, which happens when the CCP replenishment rate for X is greater than 1, the blood-type X non-prioritized patients are self-su cient, and we can distribute the remaining CCP to other compatible blood types to serve all of them.[23] Thus, assume that replenishment rate $p_X(k \quad r_X) < 1$ for at least one blood type X 2 B, as otherwise all blood types will be self-su cient and non-prioritized patients who survive donate enough CCP on net to supply future generations of patients.

Moreover, assuming $p_X(k \quad r_X) < 1$, we observe that $_X$ is the numerator and $_X$ is the denominator of $\hat{s}^n_X$ in (20)

$$\hat{s}^n_X = \frac{_X}{_X}: \tag{24}$$

Another way the excess CCP of one blood type can be used for other blood types is that if $_X > 0$ and still $_X > \; _X$. Suppose as an example, for $_O; \; _A > 0$ we have,

$$0 < \hat{s}^n_O < \hat{s}^n_A: \tag{25}$$

Since blood-type O patients can receive blood-type A CCP, for an egalitarian CCP allocation, we can give some of the blood-type A CCP to blood-type O patients and increase the service rate for O patients and decrease the service rate for A patients. Let $_{A ! O}$ be the resulting net transfer ow of blood-type A CCP to blood-type O patients.

Then, the new service rates of both types will be

$$s_O = \frac{_O + \; _{A!O}}{_O} \qquad s_A = \frac{_A \quad _{A!O}}{_A}: \tag{26}$$

We can continue increasing the net transfer $_{A ! O}$ until both service rates become equal, to sustain an egalitarian service rate among the two blood types. Either we will eventually have both service rates exceeding 1, and hence all of these patients are served, or we will end up with an equal service rate for A and O less than 1. Observe that the amount of CCP transfer from A to O that makes (26) hold with equality is

$$_{A!O} = \frac{_A \; _O \quad _O \; _A}{_O + \; _A}; \tag{27}$$

which is strictly greater than 0 (by (25)) he a/F17 111A

.9552 Tf743 4.552 0 Td [(k)a Td [( )]TJ/F49 7.18.9254 -1.793 Td [(X)]TJ/F17 11.9552 Tf 10.917 4793 Td [()]TJ/F49 7.9701 Tf 5.18

This resulting service rate, what we call the *pooling service rate* for A and O is then

$$\hat{s}^n_{\{O,A\}} := \frac{\mu_O + \mu_A}{\mu_O + \mu_A} = s_O = s_A. \tag{28}$$

Observe that (28) treats patients as if A and O together form an "composite blood type" and yet the subsidy of CCP is one way: some blood-type A CCP is used to treat blood-type O patients, but blood-type O CCP is never used on blood-type A patients (as it would not be compatible).

As $\mu_A, \mu_O, \mu_A, \mu_O > 0$, we have

$$\hat{s}^n_O = \frac{\mu_O}{\mu_O} < \hat{s}^n_{\{O,A\}} < \hat{s}^n_A = \frac{\mu_A}{\mu_A}.$$

Additionally, if the service rate for B, $\hat{s}^n_B$ is larger than the pooled rate in (28) but lower than $\hat{s}^n_A$, we can further subsidize blood-type O

will be served in full by blood-type X CCP supply. We set the service rates for those blood types to 1. Let $\mathcal{B}^0 = \{\{O\}, \{A\}, \{B\}, \{AB\}\}$ be the set of remaining blood types—where singleton sets $\{X\}$ denote that no remaining types are pooled yet. We find all individual service rates $\hat{s}^n_{\{X\}}$ as defined in (24) so that $\hat{s}^n_{\{X\}} = \hat{s}^n_X$ for each $\{X\} \in \mathcal{B}^0$. We then continue to Step 1.

⋮

Step t 1: Suppose $\mathcal{B}^{t-1}$ is the collection of pooled blood sets determined in the previous step. For each pooled set $Y \in \mathcal{B}^{t-1}$, let the service rates $\hat{s}^n_Y$ be as defined in previous steps. Suppose pooled set $X \in \mathcal{B}^{t-1}$ has the smallest service rates $\hat{s}^n_X$ among sets in $\mathcal{B}^{t-1}$. If $\hat{s}^n_X \geq 1$, then all non-prioritized patients of blood types in every pooled set in $\mathcal{B}^{t-1}$ are fully served, and we stop the procedure; otherwise, we continue.

If $\mathcal{C}(X; \mathcal{B}^{t-1}) \neq \{X\}$, let Y be the set that has the largest service rate among all pooled sets in $\mathcal{C}(X; \mathcal{B}^{t-1}) \setminus \{X\}$. Then X and Y are pooled together; we replace X and Y with their union $S = X \cup Y$, so that

$$\mathcal{B}^t := \mathcal{B}^{t-1} \setminus \{X, Y\} \cup \{S\} \tag{29}$$

and the new service rate for S (using definitions of α_X and β_X in (22) and (23)) is

$$\hat{s}^n_S := \frac{\sum_{X \in S} \alpha_X}{\sum_{X \in S} \beta_X}. \tag{30}$$

If $\mathcal{C}(X; \mathcal{B}^{t-1}) = \{X\}$, then X is not pooled with any other set. For each blood type $X \in \mathcal{X}$ the final pooled service rate is set as $\hat{s}^n_X$. We set

$$\mathcal{B}^t := \mathcal{B}^{t-1} \setminus \{X\}. \tag{31}$$

If $\mathcal{B}^t = \emptyset$, then we stop by setting any final service rate greater than 1 to 1, otherwise we continue with Step t+1.

We illustrate the pooling procedure with an example:

Example 1. Suppose initially that

$$\hat{s}^n_{\{AB\}} < \hat{s}^n_{\{O\}} < \hat{s}^n_{\{A\}} < \hat{s}^n_{\{B\}},$$

and the net demand is positive for each blood type, i.e., $\nu_X > 0$ for all $X \in \mathcal{B}$.

In Step 0, we let

$$\mathcal{B}^0 = \{\{O\}, \{A\}, \{B\}, \{AB\}\}.$$

In Step 1, the lowest service rate belongs to $\{AB\} \in \mathcal{B}^0$. There is no other blood-type CCP that

can be given to blood-type AB patients; hence,

$$\mathcal{C}(\{AB\}, \mathcal{B}^0) = \{AB\},$$

meaning that $\{AB\}$ will be pooled alone with its service rate $s^n_{\{AB\}}$. We set

$$\mathcal{B}^1 = \mathcal{B}^0 \setminus \{AB\} = \{O\}, \{A\}, \{B\}.$$

In Step 2, the lowest service rate belongs to $\{O\} \in \mathcal{B}^1$. We have

$$\mathcal{C}(\{O\}, \mathcal{B}^1) = \{O\}, \{A\}, \{B\}$$

as CCP of blood types A, B, and O can be given to blood-type O patients. The highest service rate belongs to $\{B\} \in \mathcal{C}(\{O\}, \mathcal{B}^1) \setminus \{O\}$. As a result, $\{O\}$ and $\{B\}$ are pooled together as $\{O, B\}$. We set

$$\mathcal{B}^2 = \mathcal{B}^1 \setminus \{B\}, \{O\} \cup \{O, B\} = \{O, B\}, \{A\}$$

and find the new service rate for the patients in B and O as in (24) for $S = \{O, B\}$. Here the key observation is that

$$s^n_{\{O\}} < s^n_{\{O,B\}} < s^n_{\{B\}},$$

which follows from the simple arithmetic relationship

$$\frac{a}{b} < \frac{c}{d} \Rightarrow \frac{a}{b} < \frac{a+c}{b+d} < \frac{c}{d}$$

(for $a, b, c, d > 0$).

In Step 3, two cases are possible:

1. If $s^n_{\{O,B\}} < s^n_{\{A\}}$, then
$$\mathcal{C}(\{O, B\}, \mathcal{B}^2) = \{O, B\}, \{A\},$$
as CCP of blood type A can be transfused to patients of blood type O. Thus, $\{O, B\}$ and $\{A\}$ are also pooled together as $\{O, A, B\}$ and
$$\mathcal{B}^3 = \mathcal{B}^2 \setminus \{O, B\}, \{A\} \cup \{O, A, B\} = \{O, A, B\}.$$
The procedure ends in the next step, as $\mathcal{B}^3$ is a singleton. Thus, the pooled sets are
$$\{AB\} \text{ and } \{O, A, B\}.$$

2. If $s^n_{\{A\}} \geq s^n_{\{O,B\}}$, then
$$\mathcal{C}(\{A\}, \mathcal{B}^2) = \{A\},$$
as CCP of blood types O and B cannot be transfused to patients of blood type A. Thus, $\{A\}$ is

pooled by itself and

$$B^3 = B^2 \cap \{A\} = \{O, B\}.$$

The procedure ends in the next step as B^3 is a singleton, and the pooled sets are

$$\{AB\}, \{A\}, \text{ and } \{O, B\}.$$

4.3 Related Literature

To our knowledge, this is the first paper to bring a market design approach to CCP donation. That said, we build heavily on the market design literature for kidney exchange. Within that literature, our model is most closely related paper to that of Sönmez, Ünver, and Yenmez (2020), who introduced a dynamic continuum matching model to study the effects of incentivizing compatible kidney donor-patient pairs to participate in exchange by providing increased priority in the deceased-donor queue. Our application to CCP has several important differences from the Sönmez, Ünver, and Yenmez (2020) model. Most importantly, patients and donors are distinct in Sönmez, Ünver, and Yenmez (2020), whereas in our model they are the same population. The incentive schemes we propose directly exploit the fact that patients can go on to become donors; since this is not possible in kidney exchange settings, the incentive schemes proposed by Sönmez, Ünver, and Yenmez (2020) are naturally quite different.

Our voucher scheme does, however, have parallels in the work on intertemporal incentives in kidney exchange: Veale et al. (2017) report on a kidney voucher system where an older living donor of a young patient starts a chain of kidney exchanges through donation to an incompatible pair. Since the younger patient will likely need a kidney in the future, the patient receives priority for a kidney at the end of a similar future chain if her kidney fails. Since the donor is old, the window for donation is short and the scheme helps other pairs receive transplants through chain exchanges in the present and in some sense \insures" the initial patient paired with the donor. Akbarpour et al. (2019) study unpaired kidney exchange, where a patient i can receive a kidney from patient j and the system will remember that patient j has the right to receive a kidney in the future.

Since plasma is part of blood, our work is also related to research on the design of blood markets. Slonim, Wang, and Garbarino (2014) provide a recent summary, and show that providing donors some form of non-monetary incentive, such as a medal or trinket increases donation; this fact to some extent suggests that a non-monetary incentive, in the form of a voucher, may increase CCP donation rates. Heger et al. (forthcoming) have proposed introducing a registry for prospective blood donors. There is also precedent for the formation of a centralized plasma bank during a pandemic. Delamou et al. (2016), for example, have reported on the Guinean National Blood Transfusion Center, which involved donor mobilization and plasma collection, for Ebola therapy in 2015.

Last, we note that our continuum model is related to a growing literature in matching theory that considers large-market models. Large-market models oriented towards market-design applications include those of Kojima and Pathak (2009), Che and Kojima (2010), Abdulkadiroğlu, Che, and Yasuda (2011), Azevedo and Leshno (2016), Azevedo and Hatfield (2018), and Azevedo and Budish (2019).Our steady-state analysis is also related to recent models of dynamic matching markets, such as the work

of Ünver (2010), Anderson et al. (2017), Baccara, Lee, and Yariv (2018), and Akbarpour, Li, and Gharan (2020).

5 Conclusion

In this paper, we propose a market design approach to CCP donation and distribution. Plasma donors may be given priority vouchers that can be used to give treatment priority to their loved ones; priority is also given to participants in clinical trials. Our model illustrates important possibilities: if the plasma replenishment rate is large enough to support the patients in a clinical trial, it is possible to treat all prioritized patients in equilibrium. There is also a positive spillover on non-prioritized patients. Moreover, if recovered patients are more willing to donate if they receive vouchers, introducing a voucher system strictly bene ts non-prioritized patients. Overall treatment availability expands further if we prioritize patients who pledge to \pay it forward" by donating plasma once they have recovered.

In the last two decades, collaboration between market designers and medical professionals has led to the development of organized kidney exchange clearinghouses around the world (see, e.g., Roth, Sönmez, and Ünver, 2004, 2005a,b), resulting in thousands of lives saved. Several of the key insights and tools in the kidney exchange literature have parallels with our proposed mechanisms for increasing CCP donation. For example,*non-directed donor chains*|one of the most successful innovations in kidney exchange (Roth et al., 2006; Rees et al., 2009)|involve \paying it forward." In such a chain, each participating incompatible patient-donor pair rst receives a kidney donation for their patient and at a later date their donor returns the favor by donating a kidney to another pair. These chains start with the gift of an altruistic donor, and can lead to quite long sequences of donations. Another life-saving innovation in kidney exchange involves \paying it backward" with a patient-donor pair where the patient is not ready for a transplant yet, and the donor will no longer be eligible for donation when the patient is expected to need a transplant in the future (perhaps due to donor age). Under a *kidney voucher* program, the donor donates today, and receives a transplant voucher for her donor in the future (Veale et al., 2017).

More broadly, suitably adapted market design innovations can assist with the novel challenges created by COVID-19. Given the fact that CCP is currently the preferred therapy for the virus, it is our hope that e orts that increase CCP supply can potentially save many additional lives.

Duan, Kai et al. (2020). \E ectiveness of Convalescent Plasma Therapy in Severe Covid-19 Patients."

Roth, Alvin E., Tayfun Sönmez, and Utku Ünver (2005b). \Pairwise Kidney Exchange."*Journal of Economic Theory*