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

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Abstract

Convalescent plasma is a blood product produced by recovered patients with several valuable uses, especially during public health emergencies. We develop a model of plasma donation and distribution and consider two incentive schemes to increase plasma supply based on "paying it backward" and "paying it forward" principles. Under the former, donors obtain credits that can be transferred to patients of their choosing. Under the latter, patients obtain priority for plasma-derived products in exchange for a future donation pledge. We show that both incentives generally increase overall treatment rates for all patients—not just those with credits or who have pledged.

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1 Introduction

Blood plasma is the liquid part of blood that holds blood cells and dissolved proteins. Convalescent plasma is from a patient who has recovered from a disease. Because it contains proteins produced while battling illness, convalescent plasma has several valuable medical uses. One use is convalescent plasma therapy, in which plasma is injected into a sick patient who is blood-type compatible in order to boost that patient's immune response. A second use is in formulating medical treatments like hyperimmune globulin, monoclonal antibodies, and other related prophylatics. Both uses are common during the outbreak of novel diseases, when no other treatments are available.[1]

The Covid-19 pandemic has attracted new attention to the procurement and distribution of convalescent plasma. As the pandemic has evolved, there has been on-going demand for convalescent plasma for the development of new therapies, as well as periods of acute shortage for plasma therapy as the disease spread throughout the world. By and large, the procurement of convalescent plasma from patients is decentralized: local public health authorities, hospital staff, and physicians encourage recovered patients to donate. There have only been a handful of coordinated efforts for donation, typically from hard-hit communities.[2] Several blood donation centers, including the American Red Cross and the Blood Centers of America, established procedures to collect Covid-19 convalescent plasma. These centers sell donated plasma to hospitals and pharmaceutical companies. Some donation centers have even experimented with forms of directed donation. For example, OneBlood, a Florida blood center, allows for referred donation, in which the center attempts to match donated plasma to an intended recipient, who may be a friend or family member (OneBlood, 2020). The New York Blood Center also initially allowed donations from patients from specific hospitals to be returned to be used by other patients at the same hospital (White Plains White Plains Hospital, 2020).[3]

This paper introduces and analyzes a market design approach to collecting and distributing convalescent plasma. We develop a model that jointly incorporates donation and allocation of plasma and explore two incentive schemes to increase the supply of plasma based on *pay-it-backward* and *pay-it-forward* principles. Through the pay-it-backward principle, the system "pays back" a plasma donor for her potentially life-saving donation by giving her a number of credits that can be used to obtain priority for plasma therapies of her loved ones should the need arise. Through the pay-it-forward principle, a patient receives priority access for plasma therapy in exchange for a pledge to return the favor by donating her own plasma in the near future, assuming she recovers and becomes eligible for plasma donation.[4] These features embed and formalize practices that are already informally embraced

[1] Convalescent plasma therapy was used during the 2003 SARS-CoV-1 epidemic, 2009-2010 H1N1 influenza virus pandemic, and 2012-13 MERS-CoV epidemic (EBA, 2020; Rubin, 2020). During the 1918 Spanish flu, fatality rates were cut in half for patients treated with blood plasma (see Luke et al., 2006 and Roos, 2020). Convalescent plasma has also been used to treat measles, influenza, and other infectious diseases. In fact, the first Nobel Prize in Physiology or Medicine was the 1901 prize for serum therapy (serum is the liquid left after coagulant elements are removed from plasma).

[2] Stack (2020) notes that the Orthodox Jewish community in New York City, initially hard-hit by Covid-19, have likely provided more than half of the plasma in Mayo Clinic's expanded access program as of May 2020.

[3] As of April 15, 2020, this no longer occurs.

[4] 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

by some doctors in their attempt to increase the recruitment of plasma donors (see, e.g., Rubin, 2020).

In our steady-state model of plasma donation, plasma donors may be given credits 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 plasma therapy is a function of the number of patients who have recovered (both through plasma therapy and by other means). We find that so long as the plasma 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 a result of the priority scheme, 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 credits, introducing a credit system strictly benefits 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: if patients who pledge to donate have an aggregate plasma 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 pledge to donate ex ante.

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; we then review related literature. Section 4 concludes.

2 Market Design Considerations for Plasma Donation and Distribution

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

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

The second type of incentive—which we call a *pay-it-forward* incentive—exploits the unusual feature of convalescent plasma that any patient who recovers becomes a potential plasma donor. This provides an opportunity to expand access to plasma: if we can use plasma to increase the patient recovery rate, and those recovered patients go on to donate plasma, then we can grow the plasma supply more than one-for-one. Thus, we propose to provide *second-tier priority* access to units in the incentivized plasma reserve for patients who do not have a credit but who pledge to donate plasma in the near future, in the event that they recover. Any patient who is able to fulfill her pledge through a plasma donation may

single-center paired kidney exchange of this form involved 101 donors and recipients (Pope, 2018).

also receive a number of credits, although fewer than those provided to donors under pay-it-backward incentives.

The priority tiers for access to the plasma product through the incentivized plasma reserve are then:

1. *First-tier priority*: Patients who arrive with a credit.

2. *Second-tier priority*: Patients who arrive without a credit but who pledge to donate plasma upon recovery, subject to eligibility requirements.

3. *Third-tier priority*: Any other patient who is in need of a plasma product.

Within each tier, ties are broken in a systematic way determined by the central planner. The system can be utilized to allocate plasma therapies or other plasma-derived products like hyperimmune globulin.

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

2.1 Pay-it-Backward Incentives

Some donors are purely altruistic and need no incentive to donate. But potential donors may at least in part wish to be able to donate to their loved ones.[5] For these donors, the pay-it-backward incentive can be expected to be valuable because the credit 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 difficulties arise:

1. The donor and intended recipient are *time-incompatible*: when the beneficiary needs plasma therapy, the donor is medically unable to donate.

2. The donor and intended recipient are *plasma-incompatible*: the beneficiary has antibodies for antigens in the donor's blood that makes the donation medically impossible.

3. The donor and intended recipient are *location-incompatible*: the donation is either difficult or impossible due to travel limitations.

By functioning as an in-kind medium of exchange, a credit surmounts each friction; this should naturally result in greater overall donation. And because plasma donors can donate multiple units of plasma, the resulting increase in plasma supply benefits the overall patient pool—not just credit recipients.

There are two important precedents for the credit system we envision. The first is blood assurance programs used for whole blood donation. In a blood assurance program, a donor obtains credits for a donation. These credits can be used to obtain discounts, refunds or waived feeds if a credit holder is ever to receive blood. For example, in the Cape Fear Valley system, each blood donation equals one blood credit that may be kept by the donor or transferred to a family member or friend in need.

[5]This consideration appears in donor FAQs, such as OneBlood (2020).

Blood credits are used to replace blood charges for patients in the health system (Cape Fear Cape Fear Valley, 2020). Starr (2002, p. 190) describes the important role that blood assurance programs played in the development of US blood markets in the 1960s, though they are currently less common.

The second precedent for a credit system is from 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 to 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.[6] We anticipate a potentially more substantial role for credits in plasma donation, because the risk and potential negative consequences to the donor are much lower for plasma donation than for kidney donation.

2.2 Pay-it-Forward Incentives

The pay-it-backward principle just discussed rewards plasma 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 plasma 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 benefit from pay-it-forward incentives may 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 important practical issue, but non-directed donor chains in kidney exchange show that it is surmountable. In a non-directed donor kidney exchange chain, a patient receives a kidney based on the pledge that their donor will donate a kidney to another patient in the future. It is possible that after a patient receives a kidney, their donor may renege; however, in practice this rarely occurs. Cowan et al. (2017) report that only six donors reneged over the course of 1,700 transplants. And the incentive to renege on upfront pledges may be stronger for kidneys than for plasma, since kidneys do not regenerate and require a much more invasive procedure for donation.

In our model, we allow for the possibility that a patient who pledges to donate in the future ends up not donating (for whatever reason); in the steady-state of our model, what we need is for the fulfilled plasma donation pledges to cover the flow of units used by the patients who pledge (both those who do and do not end up donating in the future).

Since pay-it-forward incentives have not been used in plasma donation before, it is difficult to estimate what fraction of patients will end up fulfilling their pledges. But in any event, the plasma replenishment rate under pay-it-forward incentives depends on (i) the rate of pledge fulfillment, (ii) how many units of plasma each patient who does fulfill a pledge donates each time she does so, and finally (iii) how many times those patients donate; of these parameters, the only one recovered patients can control is (iii).

[6]These chains were introduced by Roth et al. (2006), and the proof of concept was documented by Rees et al. (2009).

3 Model of 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 plasma donation and demand. We assume for simplicity that each patent receives plasma from a donor of the same blood type.

3.1 Paying it Backward through Priority Credit

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

We first consider a pay-it-backward incentive scheme: We suppose that each individual who donates plasma receives $v > 0$ *priority credits* that can be used to give treatment priority to family members or other close associates.[7]

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

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

Within each group priority group, plasma 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 credits are provided—i.e., $v = 0$—in which, there is a set-aside reserve for clinical-trial patients and the rest of the plasma supply is rationed among the remaining patients, with all plasma being supplied through purely altruistic donation.

We consider a continuum flow model over (continuous) time and analyze the system at a steady-state. Flow rates are defined as one-dimensional Lebesgue measures of sets of individuals that become available at each time.[8]

We suppose that there is a separate market for each blood type or the donated plasma is purified and pooled to produce hyperimmune globulin shots, which does not require blood-type compatibility for its administration.

Let τ be the flow clinical trial plasma reserve size. We assume that there is overdemand for the trial, so that a flow rate of $\pi^t = \tau$ of patients participate.

At steady-state we assume that there are patients who arrive to the medical system with the credit-prioritized status; we denote the steady-state flow arrival rate of these patients by π^v. Each of these patients hold a credit given to her by a plasma donor.

The remaining patients are non-prioritized; we denote their steady-state flow rate by $\pi^n \geq 0$.[9]

[7] We introduce the pay-it-forward incentive scheme in the next section.

[8] We denote measures of sets, i.e., flow rates, with Greek letters, while we use Latin letters for numbers and proportions.

[9] We treat $\pi^t = \tau$ as an exogenous parameter and π^n as a steady-state rate so that π^v is endogenously determined as a function of these and other population and credit system parameters at the steady-state.

Some of the patients recover without any plasma therapy; we denote the flow arrival rate of these recovering patients by ω.

The plasma therapy has steady-state arrival flow rate γ. We assume for simplicity that each patient who is treated recovers.[10]

We denote the service rates for clinical-trial patients, credit-prioritized patients, and non-prioritized patients by s^t, s^v, and s^n respectively; these are the proportions of the respective populations that are treated with plasma. The flow rates of recovery for each type of patient are then $s^t\pi^t$, $s^v\pi^v$, and $s^n\pi^n$.

Plasma can only be supplied by recovered patients. The flow rate of patients who can potentially provide plasma thus has four components: $s^t\pi^t$, $s^v\pi^v$, and $s^n\pi^n$—all described in the previous paragraph—as well as patients who have recovered without plasma therapy, with flow rate ω. We assume that recovering clinical-trial patients, recovering non-prioritized patients, and recovering patients using alternative treatment models donate plasma at the same rate p.[11] We also make a simplifying worst-case scenario assumption regarding credit-prioritized patients: we assume that credit-prioritized patients who recover do not donate plasma.[12]

Thus, the steady-state plasma therapy supply flow rate is endogenously determined by

$$\gamma = p(s^t\pi^t + s^n\pi^n + \omega)k, \tag{1}$$

where p is the probability that a given recovered patient donates and k is the number of units of plasma that patient can donate.[13]

As mentioned before, each individual who donates plasma receives $v \geq 0$ priority "credits" that can be used to give treatment priority to a family member or other close associate. Patients become credit-prioritized if, and only if, some donor allocates one of her v priority credits to them; thus, we must have

$$\pi^v = p(s^t\pi^t + s^n\pi^n + \omega)qv, \tag{2}$$

where q is the proportion of credits actually redeemed. We will use $r = qv$ to denote the average number of redeemed credits used per donor, which we call the *credit redemption rate*. We refer to

$$p(k - r)$$

as the *replenishment rate* of the plasma therapy; this is the average amount of net plasma donated to the general pool per recovered patient.

[10]Our qualitative results are the same if only a proportion of treated patients recover and only a proportion of non-treated patients die.

[11]We make this assumption for simplicity; all our results are robust to relaxing it. In particular, if recovered patients who received plasma donate at a different rate than those who did not, our analysis here provides a lower bound on the total plasma stock if we take p to equal the minimum of the two donation probabilities.

[12]If we instead assumed that recovering credit-prioritized patients donate at the same rate as the other patient groups, our Propositions 1, 2, 4 and 5 would all still hold, as donation by recovered credit-prioritized patients increases the net plasma supply, and all four results provide sufficient conditions for a priority system to function under a minimum plasma supply. The qualitative conclusion of Proposition 3 that a credit system is better than an altruistic donation scheme under Assumption 1, as well as the given sufficient condition, would also continue to hold.

[13]In the model we think of each donor as donating just once; however, the analysis is unchanged if donors can donate repeatedly and we take k to be the average total donations per-individual.

Our first result states conditions that guarantee all prioritized groups have service rate 1, i.e., $s^t = 1$ and $s^v = 1$:

Proposition 1. *So long as the plasma replenishment rate is large enough to support the clinical trial, i.e.,*

$$p(k-r) \geq \frac{\tau}{\tau+\omega}, \tag{3}$$

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

$$s^t = 1 \qquad \textit{and} \qquad s^v = 1. \tag{4}$$

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

$$\gamma \geq \pi^t + \pi^v \tag{5}$$

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

$$p(\pi^t + s^n\pi^n + \omega)(k-r) \geq \pi^t \iff k - \frac{\pi^t}{p(\pi^t + s^n\pi^n + \omega)} \geq r.$$

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

$$k - \frac{\pi^t}{p(\pi^t + \omega)} \geq r$$

as a sufficient condition for (5); this is precisely (3) since $\pi^t = \tau$ is the reserve size. □

We next turn our attention to the plasma therapy service rate s^n for non-prioritized patients, which takes the form

$$s^n = \frac{\gamma - s^t\pi^t - s^v\pi^v}{\pi^n}. \tag{6}$$

Assuming that (3) holds (i.e., $s^t = 1$ and $s^v = 1$) we substitute (1), (2), and the reserve size $\pi^t = \tau$ into (6) to find:

$$s^n = \begin{cases} \frac{\omega p(k-r) - \tau\left(1-p(k-r)\right)}{\pi^n\left(1-p(k-r)\right)} & \text{if } p(k-r) < 1 \\ +\infty & \text{if } p(k-r) \geq 1. \end{cases} \tag{7}$$

There is positive feedback: raising the number of patients who recover without plasma therapy, ω, increases the steady-state service rate—and this effect is greater the larger the probability that recovering patients donate, and the more units they contribute to the system. Naturally, the service rate is also increasing in the replenishment rate.

We see from (7) that if the plasma replenishment rate is greater than 1, we will have an arbitrarily large amount of plasma available at steady-state, so that all patients will be able to be treated. On

the other hand, even if the replenishment rate is less than 1, we may still be able treat everybody and end up with finite but excess supply of plasma; this is characterized by (finite) $s^n \geq 1$.

We note in particular that so long as (3) holds, we have

$$s^n \geq 0,$$

which leads to the following corollary:

Corollary 1. *So long as the plasma replenishment rate is large enough to support the clinical trial (i.e., (3) holds), the flow recovery rate of non-prioritized patients, $s^n\pi^n + \omega$, is weakly higher than the rate that would arise absent plasma donation, ω, even when all plasma-clinical-trial patients and credit-prioritized patients are treated ahead of non-prioritized patients.*

From (7), we compute that $s^n \geq 1$ whenever

$$p \geq \frac{\tau + \pi^n}{(\tau + \pi^n + \omega)(k - r)}. \tag{8}$$

We thus find:

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*

$$p(k - r) \geq \frac{\tau + \pi^n}{\tau + \pi^n + \omega}.$$

3.1.1 Altruistic Donation vs. Incentivized Backward Donation

Additionally, we can think of p in terms of a supply curve $p(\,\cdot\,)$ that is strictly increasing and differentiable as a function of the credit redemption rate, r. Thus, $p(0)$ refers to the altruistic donation probability (which is what would arise without any incentive scheme involving prioritization through credits).

We make the following assumption:

Assumption 1. The replenishment rate $p(r)\cdot(k-r)$ is strictly increasing at $r = 0$ (i.e., $p'(0)k > p(0)$).

Assumption 1 is fairly mild; it is satisfied if a sufficiently small percentage of recovering patients donate altruistically without any credit scheme in place. Under Assumption 1, assuming an interior maximum $s^* < 1$ (i.e., $s = 1$ cannot be achieved no matter what r is), our expression (7) for s^n implicitly defines the optimal r through the necessary first-order condition:

$$0 = \frac{ds^n}{dr} = \frac{d}{dr}\left[\frac{\omega \cdot p(r) \cdot (k - r) - \tau\big(1 - p(r) \cdot (k - r)\big)}{\pi^n\big(1 - p(r) \cdot (k - r)\big)}\right],$$

so that we have

$$\frac{p'(r^*)}{p(r^*)} = \frac{1}{k - r^*}. \tag{9}$$

Observe that the r^* in (9) is also the value that maximizes the replenishment rate $p(r) \cdot (k - r)$.[14]

[14] If there are multiple such values, we pick the one among them that achieves the highest service rate s^n.

Such an interior maximum exists for the service rate because the service rate is increasing in the replenishment rate and the replenishment rate is increasing at $r = 0$ by Assumption 1 (and hence is positive at a small $r \approx 0$); moreover the service rate falls back to 0 when r satisfies (3) with equality.

We summarize our findings with the following proposition:

Proposition 3. *Under Assumption 1, so long as the plasma replenishment rate is large enough to support the clinical trial, (i.e., (3) holds) the credit redemption rate that maximizes the plasma service rate for non-prioritized patients satisfies $r^* > 0$—that is, using a credit scheme strictly improves outcomes for non-prioritized patients.*

Moreover, the service rate for non-prioritized patients s^n is strictly increasing in the plasma replenishment rate $p(r) \cdot (k - r)$ and is maximized either

- *at $s^{n*} = 1$ by all credit redemption rates r that satisfy (8), or*
- *at some $s^{n*} < 1$ (if there is no r such that we can have $s^n = 1$) by a credit redemption rate $r^* > 0$ satisfying (9).*

3.2 Paying it Forward through a Pledge of Future Donation

We now suppose that there is also a pathway some patients can use to gain priority for treatment, which is to pledge upfront to donate plasma upon recovery. We suppose that in addition to upfront treatment, we give such a patient $v^f \geq 0$ credits after (and if) she donates plasma.[15]

As before, we set aside a reserve for clinical-trial patients with the flow capacity τ. The rest of the plasma therapy is allocated within the incentivized plasma reserve, which now has three priority classes ordered as follows:

1. patients who have credit (whom we refer to as *credit-prioritized*, as before);
2. patients who do not have credits but pledge to donate after they recover (*pledged* patients); and
3. patients not in any of the other categories (*non-prioritized* patients).

We denote the steady-state flow rate of patients participating in clinical trial by $\hat{\pi}^t = \tau$; the flow rate of credit-prioritized patients by $\hat{\pi}^v$; the flow rate of pledged patients by $\hat{\pi}^f$; and the flow rate of non-prioritized patients by

$$\hat{\pi}^n = \pi^n - \hat{\pi}^f \leq \pi^n.$$

We refer to the different types of patients' respective plasma therapy service rates as $\hat{s}^t$, $\hat{s}^v$, $\hat{s}^f$, and $\hat{s}^n$.

Then the total flow rate of recovering patients has four components:

- patients who participate in clinical trials, with a flow rate $\hat{s}^t\hat{\pi}^t$;

[15] We may also count the treatment of the pledged patient herself as the upfront redemption of a credit, in which case we would think of this patient as receiving credits to treat as many as $v^f + 1$ patients, including herself.

- patients who are credit-prioritized, with a flow rate $\hat{s}^v\hat{\pi}^v$;[16]
- patients who have pledged to donate ex ante, with a flow rate $\hat{s}^f\hat{\pi}^f$; and
- patients who are not part of clinical trials, do not have credits, and have not pledged to donate, with a flow rate of $\hat{s}^n\hat{\pi}^n + \omega$.

The total steady-state flow of plasma therapy is

$$\hat{\gamma} = \big(p(\hat{s}^t\hat{\pi}^t + \hat{s}^n\hat{\pi}^n + \omega) + p^f\hat{s}^f\hat{\pi}^f\big)k, \tag{10}$$

where p is the population probability to donate in return for credits (as in the prior sections) and p^f is the probability with which pledged patients donate upon recovery. We allow the possibility that some patients who pledge may not end up donating—perhaps due to medical ineligibility—so that p^f is expected to be less than 1. We only assume that pledging increases one's probability of donation, so that $p^f \geq p$.

We assume that patients who decide to donate ex post each receive v priority credits to be used by their loved ones, as before. On the other hand, pledged patients possibly also receive a number of vouchers upon recovery and donation—if they they donate k units of plasma, they receive v^f credits. The v^f credits are only given after the pledged recovering patient "pays it forward" by donating plasma, which occurs with probability p^f.

Thus, the flow rate of credit-prioritized patients $\hat{\pi}^v$ satisfies

$$\hat{\pi}^v = p(\hat{s}^t\hat{\pi}^t + \hat{s}^n\hat{\pi}^n + \omega)qv + p^f\hat{s}^f\hat{\pi}^f qv^f. \tag{11}$$

As before, we will work with the credit redemption rates

$$r = qv$$

for the patients who have not pledged ex ante but decide to donate upon recovery. Similarly, for pledged patients, we write:

$$r^f = qv^f.$$

The following proposition gives conditions under which we can fully serve all prioritized patient groups (i.e., so that $\hat{s}^t = 1$, $\hat{s}^v = 1$, and $\hat{s}^f = 1$):

Proposition 4. *Regardless of the pledged patient arrival rate $\hat{\pi}^f$, so long as we have*

$$p(k - r) \geq \frac{\tau}{\tau + \omega} \qquad \textit{and} \qquad p^f(k - r^f) \geq 1, \tag{12}$$

[16] As before, we conduct a worst-case analysis under the assumption that patients who have credits do not become plasma donors upon recovery. Propositions 4 and 5 continue to hold if we assume credit-prioritized patients also donate with probability p upon recovery.

it is possible to ensure that all clinical-trial patients, credit-prioritized patients, and pledged patients receive plasma therapy, so that

$$\hat{s}^n = 1, \qquad \hat{s}^v = 1, \qquad \textit{and} \qquad \hat{s}^f = 1.$$

Proof. Clinical-trial patients, credit-prioritized patients, and pledged patients are prioritized over non-pledged patients. Thus, by setting $\hat{s}^t = \hat{s}^v = \hat{s}^f = 1$ and using (10) and (11), we see that all prioritized patient groups can all be treated by plasma if

$$\hat{\gamma} \geq \hat{\pi}^t + \hat{\pi}^v + \hat{\pi}^f \iff p(\hat{\pi}^t + \hat{s}^n\hat{\pi}^n + \omega)(k-r) + p^f\hat{\pi}^f(k-r^f) \geq \hat{\pi}^t + \hat{\pi}^f. \tag{13}$$

To capture the minimum amount of plasma needed to treat all pledged patients, we consider the worst-case scenario in which no non-prioritized patients are treated, i.e., $\hat{s}^n = 0$. Then necessary and sufficient conditions for (13) to be satisfied regardless of $\hat{\pi}^f$ are

$$p(k-r) \geq \frac{\hat{\pi}^t}{p(\hat{\pi}^t + \omega)} \qquad \text{and} \qquad p^f(k-r^f) \geq 1. \tag{14}$$

Replacing $\hat{\pi}^t$ with τ in (14), we obtain (12). □

The first condition in (12) is the same condition as (3): The replenishment rate of the plasma obtained from initially non-pledged patients should be at least as large as is needed to support the clinical trial plasma reserve. The second condition in (12) requires that the replenishment rate of plasma obtained from pledged patients should at least cover those patients' own initial treatment in steady-state.

We now examine the plasma service rate for non-prioritized patients when (12) holds:

$$\hat{s}^n = \frac{\hat{\gamma} - \hat{s}^t\hat{\pi}^t - \hat{s}^v\hat{\pi}^v - \hat{s}^f\hat{\pi}^f}{\hat{\pi}^n}. \tag{15}$$

Expanding (15) assuming $\hat{s}^v = 1$, we find that

$$\hat{s}^n = \frac{\big(p(\hat{s}^t\hat{\pi}^t + \hat{s}^n\hat{\pi}^n + \omega)(k-r)\big) - \hat{s}^t\hat{\pi}^t + \big(p^f\hat{s}^f\hat{\pi}^f(k-r^f)\big) - \hat{s}^f\hat{\pi}^f}{\hat{\pi}^n}. \tag{16}$$

Solving (16) for $\hat{s}^n$ (replacing $\hat{\pi}^t = \tau$ and $\hat{s}^t = 1$), we see that, assuming the pay-it-backward credit replenishment rate does not on its own lead to infinite excess supply of plasma (i.e., $p(1-r) < 1$),

$$\hat{s}^n = \frac{\omega p(k-r) - \tau\big(1 - p(k-r)\big) + p^f\hat{s}^f\hat{\pi}^f\big(k - r^f - \frac{1}{p^f}\big)}{\hat{\pi}^n\big(1 - p(k-r)\big)}. \tag{17}$$

Comparing (17) to (7), we see that non-prioritized patients are served at a weakly higher rate than

they would be under a system that does not prioritize pledged patients whenever

$$\frac{\omega p(k-r) - \tau\big(1-p(k-r)\big) + p^f \hat{s}^f \hat{\pi}^f \big(k - r^f - \frac{1}{p^f}\big)}{\hat{\pi}^n\big(1-p(k-r)\big)}$$
$$= \hat{s}^n \geq \frac{\pi^n}{\hat{\pi}^n} s^n = \frac{\pi^n}{\hat{\pi}^n}\left(\frac{\omega p(k-r) - \tau\big(1-p(k-r)\big)}{\pi^n\big(1-p(k-r)\big)}\right).$$

Thus, we find that $\hat{s}^n \geq s^n$ when (12) holds, and conclude:

Proposition 5. *So long as (12) holds, besides treating every clinical-trial patient and credit-prioritized patient ($\hat{s}^t = \hat{s}^v = 1$), it is possible to treat every patient who pledges to donate plasma upfront ($\hat{s}^f = 1$), while still raising the service rate for non-prioritized patients who have not pledged to donate.*

3.3 Related Literature

To our knowledge, this paper is the first to propose a market design approach to plasma donation. That said, several of the key insights and tools in our proposed mechanisms for increasing plasma donation in have parallels in the kidney exchange literature (see, e.g., Roth, Sönmez, and Ünver, 2004, 2005a,b). Within that literature, our model is most closely related 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. The most important difference is that 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 exploit the fact that patients can go on to become donors unlike kidney exchange settings.

There are parallels between the pay-it-forward and pay-it-backward idea in kidney exchange. *Non-directed donor chains* involve paying it forward (Roth et al., 2006; Rees et al., 2009). In such a chain, each participating incompatible patient-donor pair first 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. Intertemporal incentives in kidney exchange also relate to the paying it backward concept. In a patient-donor pair where the patient is not ready for a transplant yet, 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). 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. Similarly, 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. Lacetera, Macis, and Slonim (2013) report that 18 of 19 different incentives in observational or field experimental studies increase blood donation. The responsiveness of blood donation to incentives suggests that a voucher may increase convalescent plasma 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, report on the Guinean National Blood Transfusion Center, which involved donor mobilization and plasma collection for Ebola therapy in 2015.

Our paper is also related to schemes used to incentivize donation of solid organs in other countries by using pledges to donate. Singapore has a presumed consent/opt-out policy for donation of cadaveric kidneys, livers, hearts, and corneas. If someone does not want to donate a particular organ, they would receive lower priority for receiving that particular organ (Singapore, 2012). In Israel, a patient who holds a donor card or is a first-degree relative with a donor card obtains priority over patients who do not. To obtain a donor card, the individual has to opt-in to donation (Lavee et al., 2010). In Chile, an individual who does not wish to donate their organ would receive lower priority for organ transplantation than a registered person if there is equal need and compatibility (Zúniga-Fajuri, 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), Azevedo and Budish (2019), Che, Kim, and Kojima (2019), and Che and Tercieux (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).

4 Conclusion

In this paper, we propose a market design approach to convalescent plasma donation and distribution. Plasma donors may be given credits 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 for non-prioritized patients. Moreover, if recovered patients are more willing to donate if they receive credits, introducing a credit system strictly benefits 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 terms of the model, there are several directions for future work. Our analysis has focused on the steady-state for analytical convenience. Since both convalescent plasma supply and demand are evolving rapidly, it will be important to understand transition dynamics leading to a steady-state. Second, we have not considered issues related to blood-type compatibility. The importance of blood-type compatibility depends on the product using convalescent plasma. For plasma therapy, plasma may be pooled across certain blood-types, raising the question of the optimal pooling strategy. We explored this issue in our earlier working paper (Kominers et al., 2020). For other investigational treatments like

hyperimmune globulin, since only a portion of the plasma is used, blood-type compatibility issues may be unimportant. Finally, we did not consider the possibility of other allocation systems, including those based on price. As far as we know, there is no current market where infected patients can buy convalescent plasma or where recovered patients can sell their plasma. However, as the market matures, these institutions may develop, and it is worth understanding how they relate to our model.

Our model has been motivated by convalescent plasma, but our ideas can apply more generally to increase supply for other human products. The key property necessary for our pay it forward incentive to work is that a patient who receives treatment can go on to become a donor in the future. There are several other products for which this property holds, including other blood components.

After we circulated the first version of this paper, we were approached by the leadership at the US Covid plasma initiative (http://covidplasmasavealife.com), a leading network of patients, donors, and hospitals about increasing plasma donation for products related to hyperimmune globulin. Though the collaboration is on-going, they have endorsed the credit system and are working to develop it in their protocols (see https://www.covidplasmasavealife.com/hig). We intend to report on these details as they develop.

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