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USING SIMULATION TO STUDY THE IMPACT OF RACIAL DEMOGRAPHICS ON BLOOD TRANSFUSION ALLOCATION POLICIES

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ABSTRACT

Managing the supply and demand of blood for transfusions is a complicated problem that many hospitals encounter since the blood supply is dependent on donations while the demand is not. Moreover, recent research also shows that transfusing older blood into patients may lead to increased mortality. This raises the issue of whether transfusing fresher blood can be achieved without jeopardizing blood availability. In this paper, we build a simulation model to study the impact of racial and ethnic diversity in combination with a blood allocation threshold. We show that for many diverse cities like New York City that the increased diversity of the population can lead to a large mismatch between blood supply and demand.

1 INTRODUCTION

Managing the supply and demand dynamics of red blood cells (RBCs) is a tough and challenging problem faced by many hospitals and cities. Not only is it important to manage the blood supply and the demand, but it is also important to make sure that the compatibility between donor and the recipient is maintained. In addition to keeping track of the quantity and the type of the available blood, it is extremely important to know the age profile of the blood as well.

Blood donations are a crucial component in many medical procedures in modern healthcare. Patients from the emergency room to the cancer ward require blood donations for survival. Blood shortages are a major problem in the United States. On an average day, Americans require 36,000 units of red blood cell donations (The American National Red Cross 2017a). However, less than four percent of Americans donate blood (The American National Red Cross 2017a). This disparity is costing hospitals millions, as they must pay to import blood due to insufficient donations to blood banks. In an attempt to minimize shortage, the current policy used for most blood transfusions throughout the United States is referred to as FIFO or "First In First Out." This policy appeals to hospitals and clinics because it minimizes wastage, so it is very cost-efficient and preserves the availability of blood for future points in time.

However, it is well known that RBCs undergo chemical changes that can have large effects on the ability of RBCs to function properly (Koch et al. 2008, Eikelboom et al. 2010, Spinella et al. 2009, Edgren et al. 2010). Thus, the age of transfused blood has been reported to be associated with an increased risk of infection, postoperative complications, and mortality (Tinmouth et al. 2006, Zallen et al. 1999, Mynster and Nielsen 2001, Offner et al. 2002, Purdy et al. 1997, Lelubre et al. 2009). Thus, the work of Fontaine et al. 2010 explored the possibility of using different allocation policies other than FIFO to distribute blood to patients. One positive feature of the threshold policy is it can provide patients with fresher blood. However, this fresher blood comes at a cost because potentially more blood can be wasted since we are using fresher blood and this can affect the availability of blood to needy patients. However,

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as we will show in the sequel, the allocation policy is not the only thing that should matter to hospitals and the dynamics of a blood supply queue. The racial demographics of a city should matter and do matter significantly.

2 OBJECTIVE AND LITERATURE REVIEW

The main objective of this work is to not only understand the impact of blood transfusion allocation policies other than the current FIFO method, but also explore the interplay and impact of the racial demographics on the allocation policy's overall dynamics of the blood supply. From analyses such as Atkinson et al. 2012, we know that allocation policies can have a profound affect on the quality of the blood, but also its availability. There are serious consequences that accompany using blood that is near expiration on patients. Older blood is linked to higher mortality, and consequential increased health risks. Previous research has also examined the tradeoff between age of transfused blood and the amount of imported blood (Atkinson et al. 2012, Simonetti et al. 2017, Simonetti et al. 2014, Dzik 2008, Fontaine et al. 2010).

One reason is that it has been shown in Atkinson et al. 2012 that a threshold policy can provide fresher blood than the current FIFO policy. Although the threshold policy is shown to waste more blood, Atkinson et al. 2012 show that this wastage is not significant enough to warrant the use of the FIFO policy, which has larger consequences on patient health. We further support this claim when cities are homogeneous racially. However, our main goal in this work is to show that racial demographics can have an significant impact on the performance of these allocation policies, especially when the population is racially diverse. In order to do so, we examined the role race plays in the blood supply queues for each blood type and explore the wastage created for different threshold policies.

Table 1: Proportions of blood types by racial/ethnic groups. (The American National Red Cross 2017b)

Race and Blood Type

Blood Type	Caucasian	African-American	Hispanic	Asian	Overall
O +	0.37	0.47	0.53	0.39	0.38
O -	0.08	0.04	0.04	0.01	0.07
A +	0.33	0.24	0.29	0.27	0.34
A -	0.07	0.02	0.02	0.01	0.06
B +	0.09	0.18	0.09	0.25	0.09
B -	0.02	0.01	0.01	0.00	0.02
AB +	0.03	0.04	0.02	0.07	0.03
AB -	0.01	0.00	0.00	0.00	0.01

It is common knowledge that there are statistically significant differences in the proportions of each blood type that vary by race and ethnicity (The American National Red Cross 2017b). Table 1 below displays a table of the proportion of African-Americans, Asians, Caucasians, and Hispanics that have each of the eight blood types $\{A^+, A^-, B^+, B^-, AB^+, AB^-, O^+, O^-\}$, and how these proportions compare with that of the entire United States population. From Table 1, it is clear that there are significant differences in blood type proportions for each racial group.

These differences are most evident in the types $\{B^+, O^+\}$. For example, Caucasians and Hispanics are half as likely as African-Americans and roughly one-third as likely as Asians to have the blood type B^+. Over half of Hispanics have the blood type O^+ while only 37% of Caucasian have this blood type. However, the blood types of different races is not the only factor for the supply of blood. One must also consider the rates at which different races donate blood as well.

While there are significant differences in the proportions of different blood types for different racial groups, there are also significant variations in the rate at which different racial groups donate blood within the United States. According to (Shaz et al. 2011) African-Americans donate blood at twice the rate of both Hispanics and Asians. However, African Americans donate at half the rate as Caucasians in the United States. Research by Shaz et al. 2008 suggests that there are two main reasons why donation rates for African Americans are lower than their Caucasian counterparts. The first reason is that many African Americans have the sickle cell trait and may have higher rates of anemia, which effectively prohibits them from donating to blood banks. Another reason is that there are often large barriers like distance to a clinic or hospital that prevent many African Americans from donating.

Table 2: Racial/Ethnic demographics of several U.S. cities given in proportions. (The American National Red Cross 2017b)

Cities by Racial Demographics

City	Caucasian	African-American	Hispanic	Asian
Baltimore, MD	0.3102	0.6155	0.0470	0.0274
Washington, DC	0.4114	0.4506	0.0989	0.0392
Bismarck, ND	0.9726	0.0074	0.0137	0.0063
New York, NY	0.3971	0.2301	0.2581	0.1146
Los Angeles, CA	0.4178	0.0805	0.4069	0.0948
Atlanta, GA	0.3813	0.5362	0.0516	0.0308
Houston, TX	0.4073	0.1911	0.3532	0.0484
Seattle, WA	0.7106	0.0808	0.0675	0.1411
Chicago, IL	0.4007	0.2930	0.2573	0.0490
Phoenix, AZ	0.5662	0.0558	0.3505	0.0275
Miami, FL	0.4459	0.1179	0.4300	0.0061
Las Vegas, NV	0.5605	0.1002	0.2843	0.0551
New Orleans, LA	0.3258	0.5943	0.0513	0.0286

Although biological reasons prevent some African Americans from donating blood, these reasons do not explain why the donation rates of Hispanics and Asians are very low and even half as low as African Americans. Research by Gillum et al. 2008 suggests that many Hispanics and Asians are just unfamiliar with the donation process and as the younger generations of Hispanics and Asians get more familiar with the process by emulating their peers, we should see their rates increase with time. Table 2 provides a table of the racial demographics of 13 major cities in the United States. One easily observes that all of these cities have different racial and ethnic demographics. As a result, it is evident that the differences in donation rates among races is also an important factor in understanding the possible blood donation supply and we should not ignore it in our modelling as it can have a significant impact on the dynamics.

Thus, the purpose of this paper is to propose a safer, more accurate blood allocation policy while taking race and ethnicity into account. Unlike previous research, we chose to factor in the racial demographics of an area into our model. This enables us to accurately account for the discrepancies between the patient and the donor populations. In using this model and varying the threshold at which blood becomes outdated, we hope to gain a better understanding of good policies for blood allocation when a given area has a diverse population.

3 THE STOCHASTIC SIMULATION MODEL

In this section, we describe the stochastic simulation model that we developed for analyzing the impact of race on blood supply dynamics. To this end, we consider each blood type as a separate, but potentially coupled and discrete time queueing process. An example figure of just one queueing process is given in Figure 1. Figure 1 also shows all of the essential flows that must be considered and accounted for in the queueing model that we construct. The leftmost first flow pictured in Figure 1 is the blood donation flow. This is the flow into the blood supply. The second and rightmost flow is the blood that departs the blood supply queue and is needed for transfusion into patients. We also have a flow (topmost) into the blood supply queue when there is not enough supply to meet the transfusion demands. This is imported from other hospitals or regions of the country. Lastly, we have a flow out of the blood supply queue that represents old blood becoming outdated and too old for use.

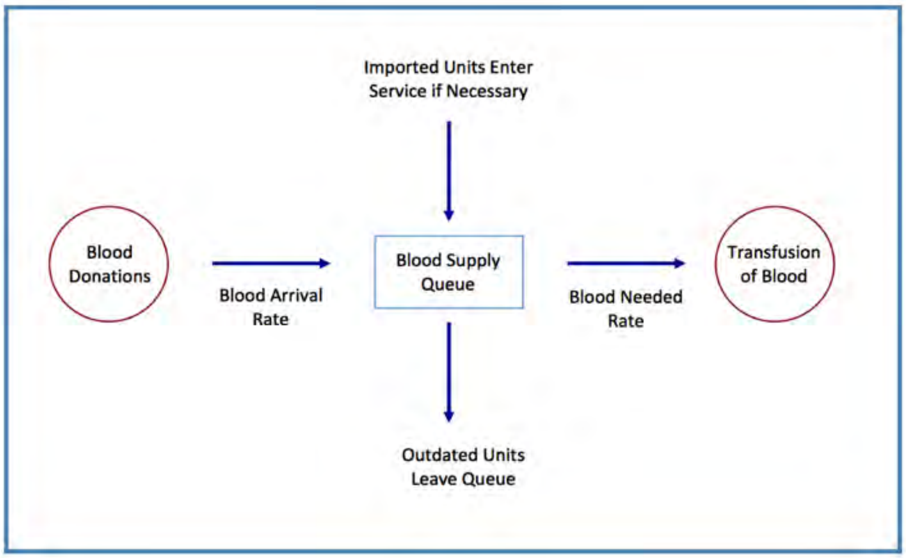

Figure 1: A Diagram of Blood Flow Through a Hospital Network.

However, there are eight blood types and thus, we have eight queues and each queue keeps a count of how many pints of blood of a certain age are available for transfusions. Figure 2 gives a pictorial representation of this queueing process. Since we use a discrete time queueing process, the unused blood units move to the right until they expire. At any point in time, these blood units can be used by patients that are compatible and need them. Moreover, Figure 3 shows a screenshot of the simulation that we built in Matlab that enabled us to do our analysis in this work. On the x-axis of Figure 3, we plot the age of blood. On the y-axis, we plot using a color scheme that represents the number of pints that are available at a specific age and blood type. As the age of the blood increases if it is not used, the available blood moves to the right by one unit of time. To get a better sense of this movement over time, a video example of this simulation is available at the following url: https://people.orie.cornell.edu/jpender/.

With this simulation model, we assume that blood is allowed to remain in the queue for 42 days and after this time the blood must be discarded. Our value for the blood age limit is consistent with current hospital practice and legal regulations. Since we are using a queueing process, it is vital to understand how the blood flows through this queueing process. Thus, we must describe the arrival process, departure process, and allocation policy of the blood queueing process in order to understand its dynamics.

As for the arrival process, we assume that the blood is donated in individual pints its number is given by a Poisson random variable with mean λ_{type} where the type corresponds to the blood types

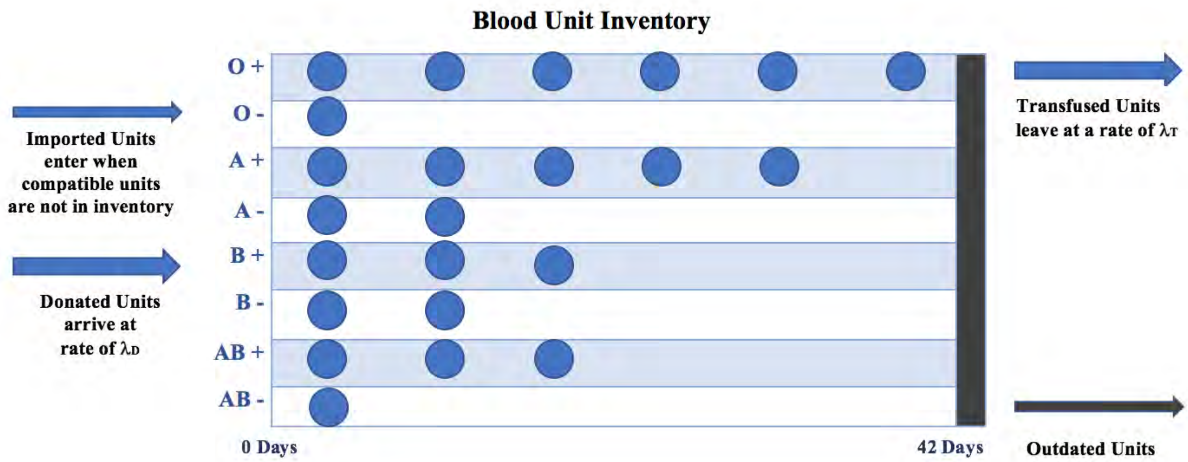

Figure 2: Dynamic Representation of Queueing Model.

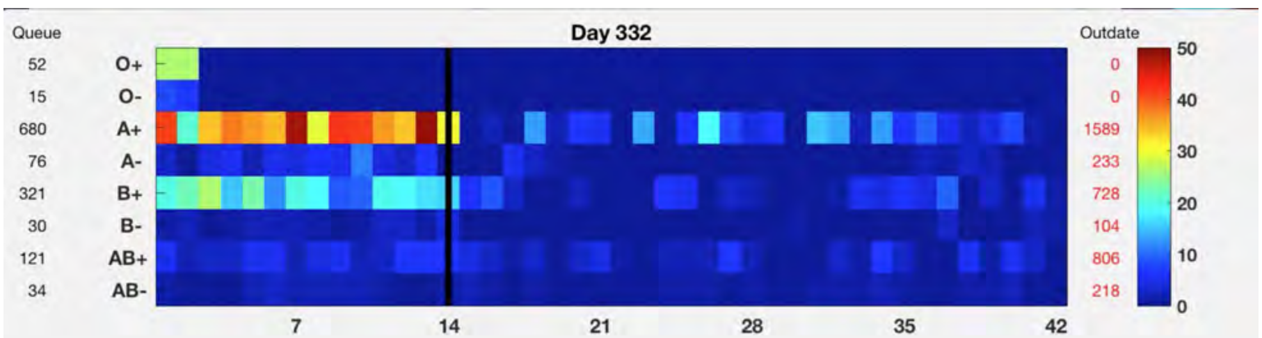

Figure 3: Screenshot of Matlab Blood Queue Simulator.

$\{A^+, A^-, B^+, B^-, AB^+, AB^-, O^+, O^-\}$. A Poisson random variables were also used in (Atkinson, Fontaine, Goodnough, and Wein 2012) and we do not change this assumption here since it is not the main point of our work. One can use other random variables for the arrival process, however, it is well known that any process models single jumps and random counting process with independent increments is equivalent to saying that the arrival model is a non-homogeneous Poisson process. Moreover, since some of this blood is discarded for quality control purposes, we assume this is negligible. We also assume that when fresh blood is donated its age starts at 1. Although sometimes blood quality must be checked for quality control purposes, we also assume that the corresponding time is negligible.

The departure process is somewhat more complex than the arrival process. We also assume that the number of blood pints needed in any given day is given by a Poisson random variable with mean μ_{type} where the type corresponds to the blood types $\{A^+, A^-, B^+, B^-, AB^+, AB^-, O^+, O^-\}$. Unlike the arrival process, the departure process is inextricably linked with the allocation policy and the donor compatibility. Figure 4 provides a picture of donor compatibility and it is clear that this will have an impact on the departure dynamics. Blood types that are more compatible are likely to experience more shortages since they will be taken from other types that have shortages. Since these dynamics of the departure process are quite complex, it is important to give an algorithm that describes the departure process and its connection with the threshold allocation policy. After setting a threshold policy, the algorithm for searching and giving away a pint of blood is as follows:

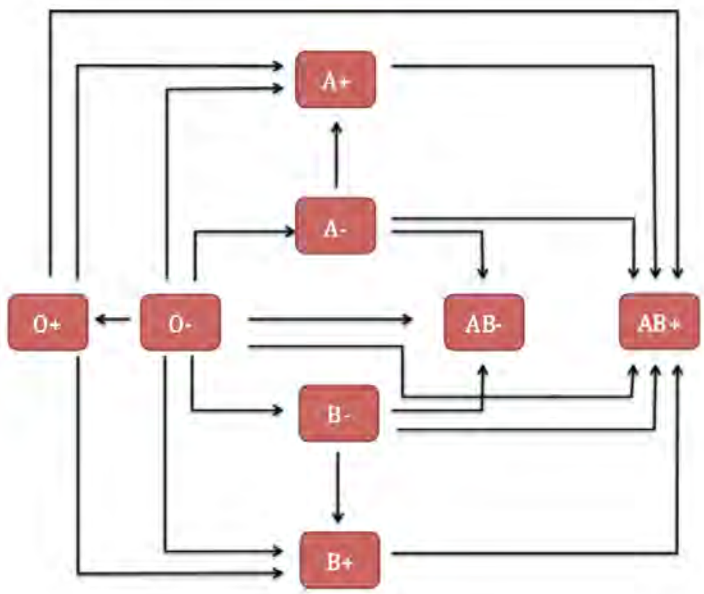

Figure 4: Donor Compatibility Diagram

- **First we look for an exact blood match**: This is done by first searching for the oldest unit of blood equal to or below the set threshold. If no blood is found, then search for the youngest unit of blood above the threshold.
- **If no exact match is found, then search for a compatible blood match**: This is done by finding the compatible blood type that has the most units to offer and once a type is chosen, we search for the oldest unit of compatible blood equal to or below the set threshold. If no blood is found, then we search for the youngest unit of compatible blood above the threshold.
- **No exact or compatible blood is found**: If no exact or compatible blood match is found, then we import the blood to fill our demand.

4 RESULTS

To understand the impact of race on the supply of blood, we select 13 major cities in United States and used their racial demographics from DeNavas-Walt et al. 2010 to produce simulations of each of their blood supply queues. Table 2 shows the proportion of each race in each city that we consider for our simulations.

Our model is general enough to accommodate for situations where individual patients need either single or multiple units of blood. Our simulation is performed using Matlab where we view the blood arrival rate and blood needed rate as independent Poisson random variables. When determining which blood unit to provide to the patient, we assign the oldest blood unit that matches the patient's blood type. If there are no units of the same blood type available, then the patient is assigned to the oldest unit of a compatible blood type. Blood units are only imported if there are no matching or compatible units in the blood supply queue. We then recorded the amount of imported units and outdated units of each blood type.

With our Matlab simulator, we produced the simulations of the blood supply queues for a total of 500 days for the following cities: Baltimore, Washington D.C., Bismarck, New York City, Los Angeles, Atlanta, Houston, Seattle, Chicago, Phoenix, Miami, Las Vegas, and New Orleans. We ran the simulations with thresholds of 14, 28, and 42 (FIFO) days to examine the effects of blood allocation policies that maximize patient health and minimize monetary cost to hospitals. We also examined the differences during times of blood shortages and surpluses by using donors-to-patients ratios that ranged from 0.9 to 1.1. To model the dependence of donor rates on racial demographics, we selected the racial donor ratio for each city to be (2:1:4:1) (African-American : Asian : Caucasian : Hispanic). This ratio was has observed in the work of Shaz et al. 2011 and seems to be robust to spatial factors in many cities.

Figure 5 shows the number of blood units that became outdated and were imported at three different donation rates in Bismarck, Baltimore, Miami, New York, and Seattle, cities with very different populations.

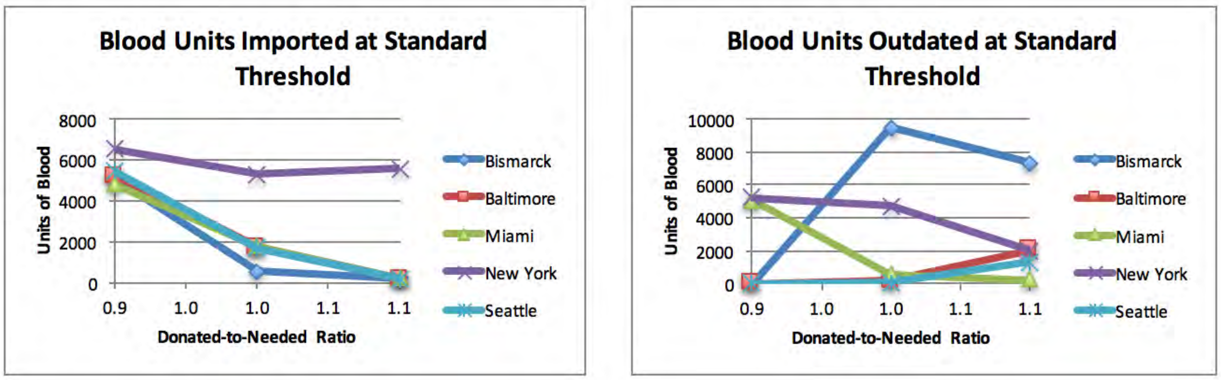

Figure 5: Varying the Donor to Patient Ratio in Bismarck, Baltimore, Miami, New York City, and Seattle.

The demographic differences in Bismarck, Baltimore, Miami, New York, and Seattle are evident in the dissimilarities in the plots of each city. In a predominantly Caucasian city like Bismarck, shown with the double line above, more donations result in more wastage. However in the cities with diverse populations, the units of blood that expire decrease as the rate of donations increase because the demand of the minority patients is satisfied. Similarly, for all cities, a higher donated-to-needed ratio yields lower amounts of blood that needs to be imported. Very diverse areas, like New York City, which is the dotted line above, have the highest import rates.

Figure 3 shows the results of the simulation for the most and least diverse cities in the study, New York and Bismarck, when the incoming rate of donated units is equal to the rate at which patients need the blood i.e $\lambda = \mu = 100$. These parameter values where chosen for simplicity, however, they are also reason able for a medium sized city in the U.S. since the U.S. needs about 36,000 pints per day (The American National Red Cross 2017a).

When we fixed the arrival rate and varied the threshold from 14 to 42 days, there were significant differences in the change in outdated and imported units in each city. Isolating the most and least diverse cities in the study, New York and Bismarck respectively, it is evident that New York has not only a higher number of outdated units, but also a higher number of imported units at all thresholds. Thus, from our simulation we observe that cities with higher diversity have more imported units and far more outdated units than those with higher homogeneity. The lower donation rates of minorities, especially Asians and Hispanics, yield blood inventories that reflect the blood types of a Caucasian population. Thus, more diverse cities have higher rates of importation and even higher rates of wastage and caution should be taken when implementing these type of threshold allocation policies in diverse cities.

Table 4 shows the results of the simulation of the four largest cities: New York, Los Angeles, Chicago, and Houston. New York City has the most diverse population of all the thirteen cities in this study. Thus, due to the large minority population, there is the greatest mismatch in the donors and recipients. Los Angeles has a large proportion of Hispanics, so there is a significant amount of outdated and imported blood. Chicago and Houston have similar demographics with minorities making up about sixty percent of the population. Likewise, these cities have a large amount of blood that becomes outdated and larger

Table 3: Comparison of Diverse and Homogeneous Populations Bismarck vs. New York City. The two most right columns in this Table represent simulated values.

City	Percent Caucasian	Percent Black	Percent Hispanic	Percent Asian	Threshold	Total Outdated	Total Imported
Bismarck, ND	97.26	0.74	1.37	0.63	14	115	909
New York, NY	39.71	23.01	25.81	11.46	14	3741	4814
Bismarck, ND	97.26	0.74	1.37	0.63	28	0	1176
New York, NY	39.71	23.01	25.81	11.46	28	3070	4726
Bismarck, ND	97.26	0.74	1.37	0.63	42	0	580
New York, NY	39.71	23.01	25.81	11.46	42	2704	5285

amounts of imported blood units. For all four cities, with each increase to the threshold, the number of outdated units decreases. There is not a significant change in the number of imported units.

In Table 5, we see the amount of imported and outdated units for Phoenix, Seattle, Washington DC, and Las Vegas, the second largest cities in the study. Washington DC has the largest minority population at about 55 percent, followed by Phoenix and Las Vegas, at about 44 percent, then Seattle at about 29 percent. While Washington DC has a larger proportion of minorities than Phoenix, it has a smaller amount of imported and outdated blood units. This is because Washington DCs minority population is predominantly African-American and Phoenix's largest minority group is Hispanic. Hispanics are half as likely to donate blood as African-Americans, so in cities with large Hispanic populations, we see more wastage and importation. In Las Vegas, which also has a significant Hispanic population, we see a similar trend. Seattle, as the city with the lowest minority proportion, has far lower amounts of imported and outdated blood at all three thresholds.

Table 6 shows the number of imported and outdated units for Baltimore, Atlanta, Miami, New Orleans, and Bismarck. The cities Baltimore, Atlanta, and New Orleans have similar racial demographics, of over 50 percent African-American, just over 30 percent Caucasian, 5 percent Hispanic, and 3 percent Asian. They have similar amounts of imported and outdated blood units with each of the three thresholds. Miami has a large Hispanic population, so there is a large amount of blood unit wastage and importation, particularly at lower thresholds. Bismarck has far lower amounts of outdated blood and imported blood, compared to the other cities. This is because Bismarck is homogeneous, so fewer donor/receiver mismatches occur.

5 CONCLUSION AND FUTURE WORK

In this paper we have investigated the impact of racial demographics in conjunction with blood allocation threshold policies. We observe from our simulations that more diversity can cause blood banks to import much more blood and waste more blood at the same time since there is a supply and demand mismatch. This effect of the racial demographics is further buttressed when the allocation policy threshold is lower. Thus, we recommend some caution when trying to implement new blood allocation policies as racial demographics can have a large negative impact on the dynamics of the blood supply.

A useful extension would explore the effects of partitioning patients into different priority classes. These classes can be based on their triage level, health condition, age, or other factors. With this type

Table 4: Imported and Outdated Blood vs. Allocation Threshold for New York City, Los Angeles, Chicago, and Houston.

City	Percent Caucasian	Percent Black	Percent Hispanic	Percent Asian	Threshold	Total Outdated	Total Imported
New York, NY	39.71	23.01	25.81	11.46	14	3741	4814
Los Angeles, CA	41.78	8.05	40.69	9.48	14	980	2044
Chicago, IL	40.07	29.30	25.73	4.90	14	844	1776
Houston, TX	40.73	19.11	35.32	4.84	14	806	1820

City	Percent Caucasian	Percent Black	Percent Hispanic	Percent Asian	Threshold	Total Outdated	Total Imported
New York, NY	39.71	23.01	25.81	11.46	28	3070	4726
Los Angeles, CA	41.78	8.05	40.69	9.48	28	659	1853
Chicago, IL	40.07	29.30	25.73	4.90	28	424	1532
Houston, TX	40.73	19.11	35.32	4.84	28	576	1883

City	Percent Caucasian	Percent Black	Percent Hispanic	Percent Asian	Threshold	Total Outdated	Total Imported
New York, NY	39.71	23.01	25.81	11.46	42	2704	5285
Los Angeles, CA	41.78	8.05	40.69	9.48	42	519	1814
Chicago, IL	40.07	29.30	25.73	4.90	42	448	1790
Houston, TX	40.73	19.11	35.32	4.84	42	427	1532

Table 5: Imported and Outdated Blood vs. Allocation Threshold for Phoenix, Seattle, Washington D.C., and Las Vegas.

City	Percent Caucasian	Percent Black	Percent Hispanic	Percent Asian	Threshold	Total Outdated	Total Imported
Phoenix, AZ	56.62	5.58	35.05	2.75	14	1221	1644
Seattle, WA	71.06	8.08	6.75	14.11	14	617	1352
Washington, DC	44.59	43.00	11.79	0.61	14	665	1557
Las Vegas, NV	56.05	10.02	28.43	5.51	14	922	1424

City	Percent Caucasian	Percent Black	Percent Hispanic	Percent Asian	Threshold	Total Outdated	Total Imported
Phoenix, AZ	56.62	5.58	35.05	2.75	28	583	1810
Seattle, WA	71.06	8.08	6.75	14.11	28	203	1443
Washington, DC	44.59	43.00	11.79	0.61	28	362	1408
Las Vegas, NV	56.05	10.02	28.43	5.51	28	511	1831

City	Percent Caucasian	Percent Black	Percent Hispanic	Percent Asian	Threshold	Total Outdated	Total Imported
Phoenix, AZ	56.62	5.58	35.05	2.75	42	484	1681
Seattle, WA	71.06	8.08	6.75	14.11	42	7	861
Washington, DC	44.59	43.00	11.79	0.61	42	196	1350
Las Vegas, NV	56.05	10.02	28.43	5.51	42	509	1894

Table 6: Imported and Outdated Blood vs. Allocation Threshold for Baltimore, Atlanta, Miami, New Orleans, and Bismarck.

City	Percent Caucasian	Percent Black	Percent Hispanic	Percent Asian	Threshold	Total Outdated	Total Imported
Baltimore, MD	31.02	61.55	4.7	2.74	14	705	1171
Atlanta, GA	38.13	53.62	5.16	3.08	14	3868	4821
Miami, FL	44.59	11.79	43	0.61	14	1463	2194
New Orleans, LA	32.58	59.43	5.13	2.86	14	574	1695
Bismarck, ND	97.26	0.74	1.37	0.63	14	115	909

City	Percent Caucasian	Percent Black	Percent Hispanic	Percent Asian	Threshold	Total Outdated	Total Imported
Baltimore, MD	31.02	61.55	4.7	2.74	28	262	1348
Atlanta, GA	38.13	53.62	5.16	3.08	28	3303	5219
Miami, FL	44.59	11.79	43	0.61	28	808	1867
New Orleans, LA	32.58	59.43	5.13	2.86	28	376	1298
Bismarck, ND	97.26	0.74	1.37	0.63	28	0	1176

City	Percent Caucasian	Percent Black	Percent Hispanic	Percent Asian	Threshold	Total Outdated	Total Imported
Baltimore, MD	31.02	61.55	4.7	2.74	42	260	1982
Atlanta, GA	38.13	53.62	5.16	3.08	42	2167	5227
Miami, FL	44.59	11.79	43	0.61	42	689	1788
New Orleans, LA	32.58	59.43	5.13	2.86	42	221	1281
Bismarck, ND	97.26	0.74	1.37	0.63	42	0	580

of information, hospitals can make better decisions regarding the transfusion of blood into patients and improve the overall health of patients.

Another extension would be to consider non-stationary arrival rates of blood donations and blood requests. The work of Massey and Pender 2013, Pender 2014, Engblom and Pender 2014, Pender 2015, Pender et al. 2017b Pender et al. 2017a, Ko and Pender 2017 seems promising in helping design a non-stationary version of our model. A non-stationary model would help in analyzing the percentage of wasted or imported blood during blood drives or a mass casualty event. We hope to analyze all of these extensions in future work.

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