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Approximate dynamic programming modeling for a typical blood platelet bank

U. Abdulwahab *, M.I.M. Wahab

Department of Mechanical and Industrial Engineering, Ryerson University, 350 Victoria St, Toronto, Ontario M5S 3G8, Canada

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ABSTRACT

This paper introduces a workable model for the establishment of an inventory bank holding perishable blood platelets with a short shelf life. The model considers a blood platelet bank with eight blood types, stochastic demand, stochastic supply, and deterministic lead time. The model is formulated using approximate dynamic programming. The model is evaluated in terms of four measures of effectiveness: blood platelet shortage, outdating, inventory level, and reward gained. Moreover, several alternative inventory control policies are analyzed. The order quantity decision is taken using a news-vendor model. In addition, the variation of the O− percentage is studied. This study confirms that the blood platelet bank reward can be maximized by operating at the optimal inventory level, thereby minimizing the number of outdated units as well as shortages. In addition, the suitable O− percentage within the blood platelet bank inventory was studied. As the O− blood type inventory levels increase to 40%, shortages drop from 3.9% to 1.5%. Outdated units drop from 4.6% to 1.8%. Furthermore, when the order quantity is received twice a day, shortages drop to 1.8% and outdated units drop to 2.1%.

1. Blood platelets and blood bank

Blood platelets (PLTs) are a very precious resource. Currently, the only source of blood platelets is that of healthy, generous adults who are willing to donate their blood for their own use or the use of others. Different products can be derived from whole blood (WB) and the most important and valuable are the blood platelets. About 20% of whole blood can be extracted as blood platelets (Blood Center, 2003). Due to age and health requirements, only about 60% of the population of the United States of America is eligible to donate blood (American Blood Center, 2011). Currently, less than 5% of those who are eligible actually donate each year. In Canada, blood platelet banks and hospital blood platelet banks account for approximately 88% of the nation's blood platelet supply (Canadian Blood service, 2011).

Different methods are used to categorize the blood. The two most well-known methods are the ABO blood platelet system and the Rhesus system. ABO divides the blood types into four types: A, B, AB, and O. The Rhesus system gives positive (+) and negative (−) signs to blood. Together they give the eight major blood platelet types seen as most relevant by medical professionals: AB+, AB−, A+, A−, B+, B−, O+, and O−. While a patient should receive blood platelets of the same type, blood platelet substitution is possible between certain blood platelet types. Table 1 shows all the substitution possibilities for all blood types, where 1 indicates that the substitution is allowed between these two blood types. 0 means that substitution is not allowed between these two blood types. Fig. 1 summarizes the blood bank inventory process. It starts with the collection and preparation of blood platelets that are then kept in the inventory. The inventory serves the internal demand using a defined policy. If it is not serving the internal demand, the blood bank may send an emergency shipment of pre-ordered platelets to a neighboring hospital or ship. Part of the assigned platelets are used and the unused platelets are returned to the inventory. Blood platelets are perishable and must be used within six-days. Consequently, a surplus older than six days in the blood platelet supply must be discarded. Whenever there is a shortage, a special search must be conducted to locate the required blood platelets and/or look for new donors. Therefore the inventory of these blood platelets needs to be pro-actively managed.

1.1. Related literature

In Europe, a report covering 14 countries found that about 44% of transfused PLTs are derived from buffy coat (BC); 49% are derived from apheresis (single-donor blood); and 7% are derived from platelet-rich plasma (PRP) (Murphy, 2005). In contradistinction, within

* Corresponding author.
E-mail address: osamasaleh22346@gmail.com (U. Abdulwahab).

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Table 1
Blood platelet substitution relationship.

Type	Demand							
Donor	AB+	AB−	A+	A−	B+	B−	O+	O−
AB+	1							
AB−	1	1						
A+	1	0	1					
A−	1	1	1	1				
B+	1	0	0	0	1			
B−	1	1	0	0	1	1		
O+	1	0	1	0	1	0	1	
O−	1	1	1	1	1	1	1	1

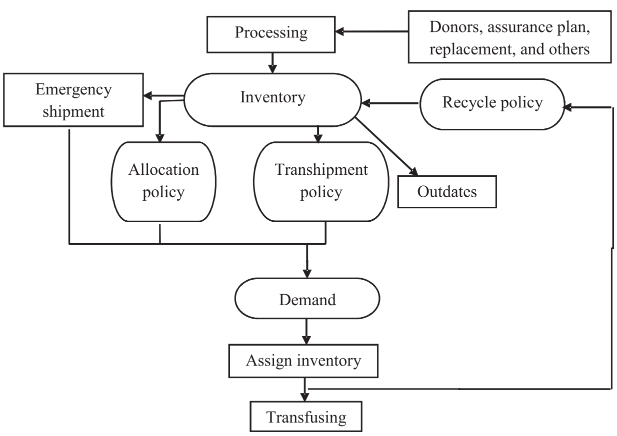

Fig. 1. Network for blood PLT inventory at day *t*.

Canada about 16% of transfused PLTs are derived from BC and 84% are derived from apheresis. Canada is attempting to reach the state where 100% of transfused PLTs are derived from apheresis (Canadian Blood Services, 2009). Moreover, the annual PLT production volumes are to some extent associated with the rate at which PLTs become outdated. PLTs are wasted throughout the supply chain. Most of the losses of PLTs are due to expiration dates. The short shelf life and uncertain demand for PLTs emphasizes the importance of managing both economic and human resources at blood establishments. A 2011 US survey Whitaker (2012) found that PLT production had increased by 13% to 4277 thousand doses over the period from 2008 to 2011. Blood centers collected 92.1% of PLTs. The outdated percentage of PLTs derived from whole blood was 19.9%, while the outdated percentage of apheresis PLTs was 13.8%. Additionally, the survey showed that the mean PLT age was 3.96 days at transfusion (Whitaker, 2012). In their 2009 annual report, the Canadian Blood Services stated that PLT collections increased 9.6% in 2008 and 2009. The order fill rate percentages were reported as 97.6% in 2007, 97.2% in 2008, and 97.7% in 2009 (Canadian Blood Services, 2009). Their 2012 annual report shows that the total PLT volume shipped to hospitals rose from 91,600 doses in 2004 and 2005 to 119,528 doses in 2011 and 2012. This showed an increase of about 30% over eight years. The demand was expected to increase by approximately 4.6% the next year (Canadian Blood Services, 2012).

There is a large body of research detailing various possible methods for blood bank optimization. Some of those include: the inventory model (e.g., Fontaine, Chung, Erhun, & Goodnough (2010) and Belin & Force (2012)); simulation (e.g., Ying (2011) and Hess & Grazzini (2011)); the Markov chain model (e.g., Haijema, Van DerWal, Dijk, & Sibinga (2008) and Ma & Powell (2008)); dynamic programming (e.g., Nguyen, Goebel, Schober, KlÃter, & Panzer (2010) and Zhou, Leung, & Pierskalla (2011)); and blood bank policies (e.g., Stanger, Wilding, Yates, & Cotton (2002) and Neurath, Cober, & Giulivi (2012)).

Because any solution should consider the various blood types and their potential ages, it is computationally expensive to find an optimal solution in a short period of time using methods such as dynamic programming. Hence, most researchers have opted for approximations and/or heuristic solutions. For example, Katz, Carter, Saxton, Blutt, and Kakaiya (1983) built a simulation that generated daily orders and calculated the mean demand. This information was used to calculate the order quantity on a daily basis. The model was found to be applicable within a 5 day storage life parameter for PLTs regardless of the varying logistics of PLT production and distribution. Blake et al. (2003) concluded that a Markov dynamic programming approach is feasible, and may lower costs by 18% while decreasing the number of outdated units and shortage rates. Prastacos (1979) and Kopach (2004) also developed a two-stage multi-echelon model with rotation units under a First In, First Out (FIFO) policy. Their approach meant that the probability of shortage was shared equally amongst hospitals. As a result, the model succeeded in reducing the number of outdated units and shortages experienced by each hospital. Haijema, Van DerWal, and Dijk (2007) also used a Markov dynamic programming and simulation approach with data from a Dutch blood bank. After some simplification of the state space (i.e., downsizing the dimension), the authors determined that an order-up-to-rule policy would perform well. The authors claimed that adding the eight blood types to the model after considering their age would not affect the final solution. A double order-up-to-rule model has two order-up-to levels, one corresponding to younger PLTs and the other to the total inventory. The model is almost optimal when medical requirements dictate that younger PLTs should be used instead of older ones. Another study by Haijema et al. (2008) considered the inventory control of blood PLTs as a multi-dimensional Markov decision problem. As their model is too large to solve optimally by exploiting the problem structure, an approximate solution is obtained by using a stochastic dynamic programming method. Ghandforoush and Sen (2010) found that due to the production costs and short shelf life of PLTs, it is not practical to build large inventories during periods of low demand or when donor supply is high. As a result, production must closely mirror demand. Furthermore, Blake et al. (2003) and Broyles, Cochran, and Montgomery (2013) built a model for blood PLT suppliers while assuming that supply is deterministic.

Moreover, some existing models are dynamic programming models that have often been dismissed because they suffer from the 'curse of dimensionality'. There are other methods that may be used to solve a dynamic programming model such as approximate dynamic programming (ADP). ADP is an extension of Dynamic Programming and Bellman's equation. Powell (2007), Powell (2010), Powell (2011a), Powell (2011b) and Powell (2011c) proposed the application of approximate dynamic programming (ADP) methods for a blood bank inventory model. ADP can cater to various model state variables while overcoming both dimensionality and time parameters, thereby removing the need to downsize. More research using ADP includes Topaloglu and Powell (2005), Powell and Roy (2005), George and Powell (2006), Topaloglu and Powell (2006), Nascimento and Powell (2008), Ma and Powell (2008), George, Powell, and Kulkarni (2008), Nascimento and Powell (2009). Abdulwahab and Wahab (2013) implemented the ADP approach suggested by Powell (2007) in a typical blood bank inventory model. The result was reasonable, and if one adds more constraints to the model and improves the policies, one will receive a favourable result.

However, Blake (2009) pointed out that it is incorrect to assume that the age distribution cannot impact optimal ordering decisions. It is necessary to develop favourable, fast, and robust models to study the PLT inventory problem. Accordingly, because the problem has a very large number of state variables, outcome spaces,